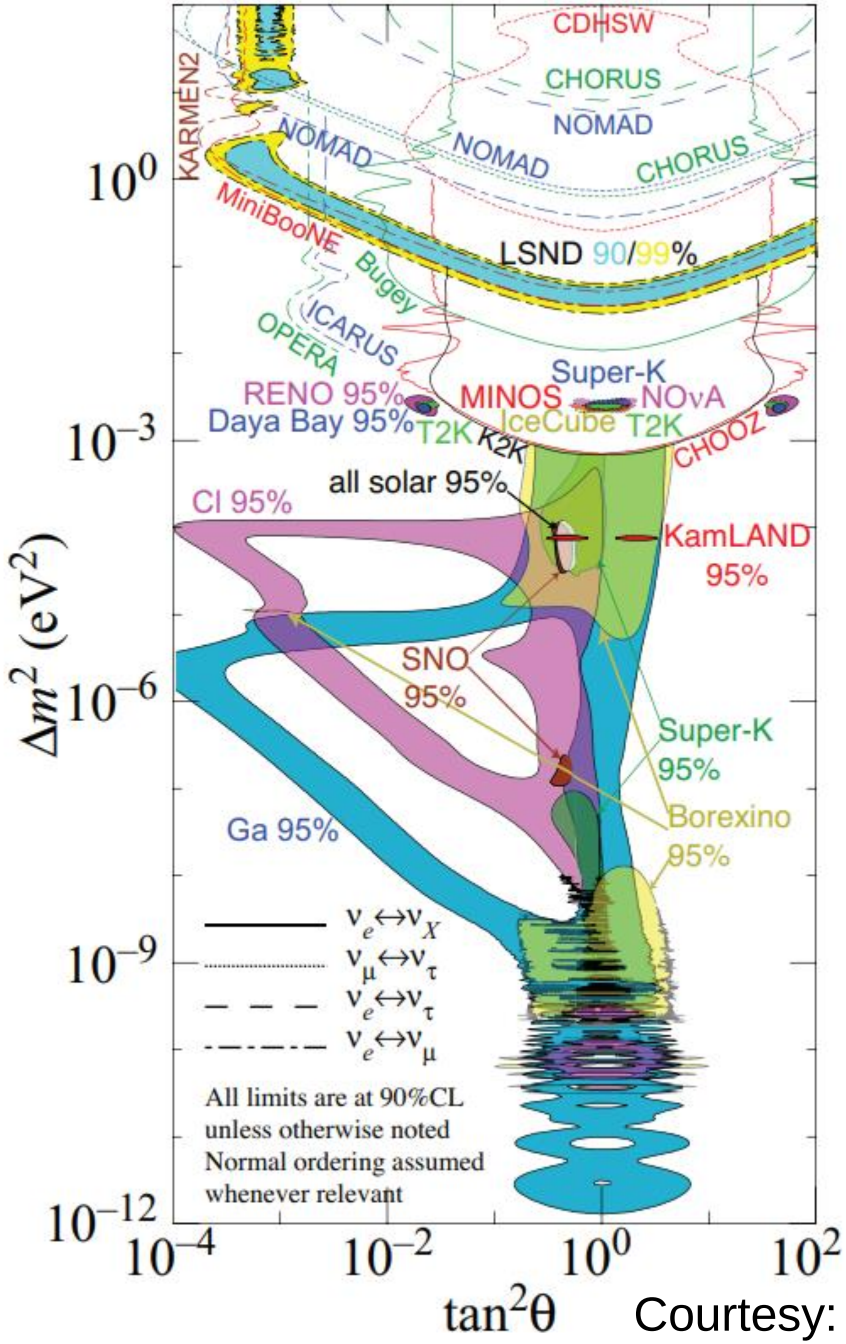
Search for an Anomalous Excess of Electron Neutrino Interactions in MicroBooNE and New Constraints on eV-Scale Sterile Neutrinos

Xiangpan Ji (BNL)

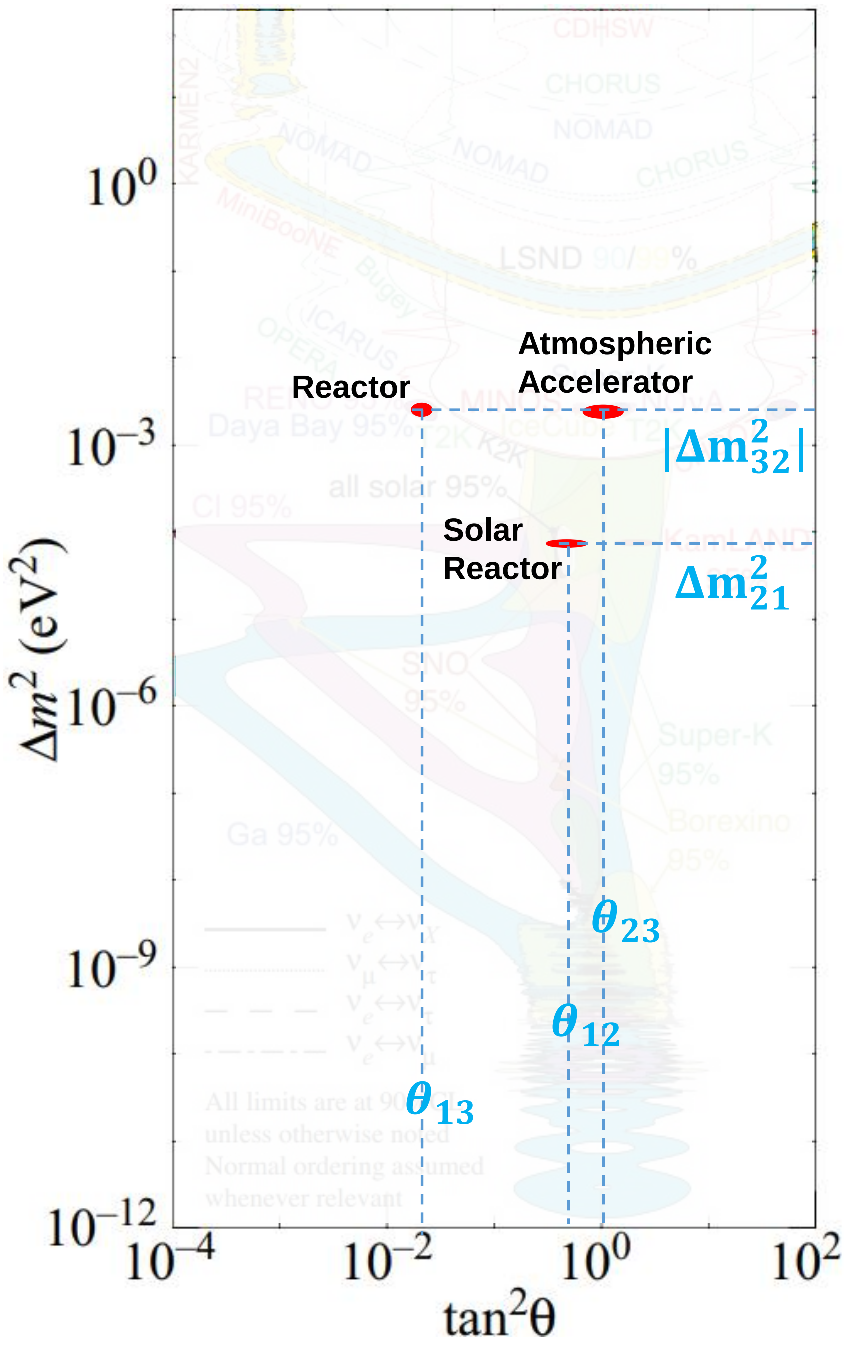
On behalf of the MicroBooNE collaboration

Neutrino Oscillation Experiments



Courtesy: Hitoshi Murayama

- > 50 years
- > 30 experiments
- > Phase space over tens of orders of magnitude



- Majority of the experimental results are consistent with the “standard” three-flavor neutrino framework

- Several “anomalies" hint at least an additional flavor of neutrinos -- eV-scale light sterile neutrinos

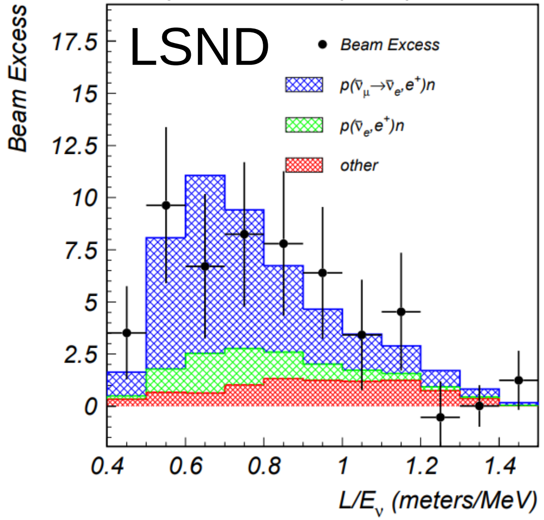
Experimental Anomalies

Experiment	Channel
GALLEX/SAGE, BEST (radioactive source), Gallium anomaly	$\nu_e \to \nu_e$
Neutrino-4 reactor expt.	$\bar{\nu}_e \to \bar{\nu}_e$
LSND anomaly	$\bar{\nu}_\mu \to \bar{\nu}_e$
MiniBooNE anomaly	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_e$

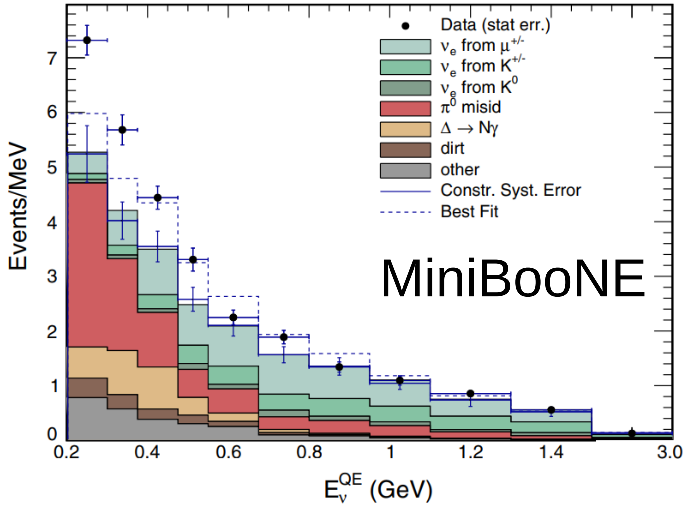
Anomalies:

- Neutrino disappearance expts: **more deficit than expectation**
- Neutrino appearance expts: **more excess than expectation**

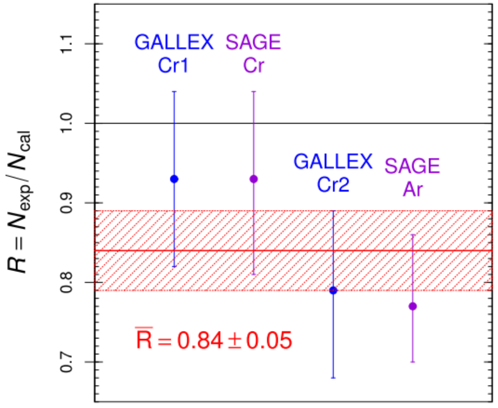
Phys. Rev. D64 (2001) 112007



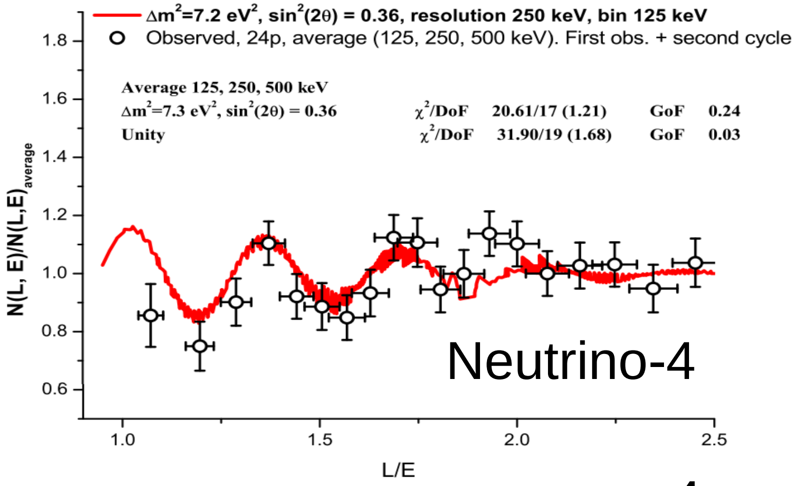
Phys. Rev. D103 (2021) 052002



GALLEX/SAGE



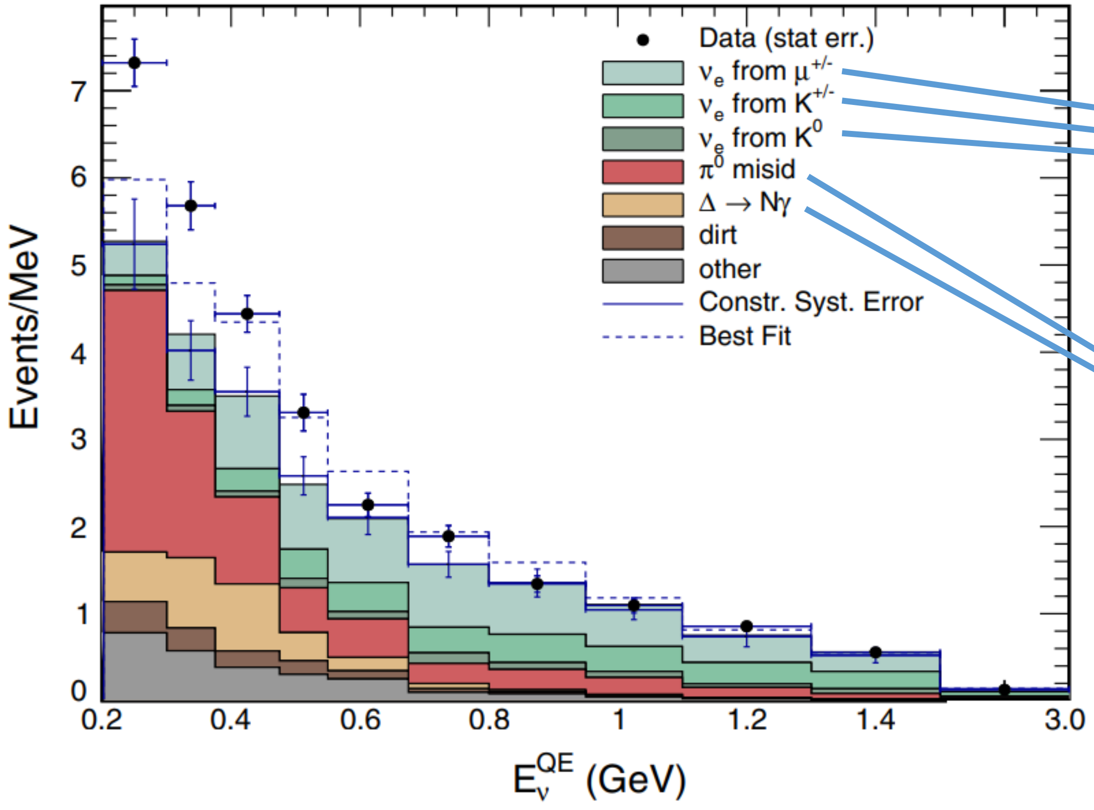
J.Phys.G 43 (2016) 033001

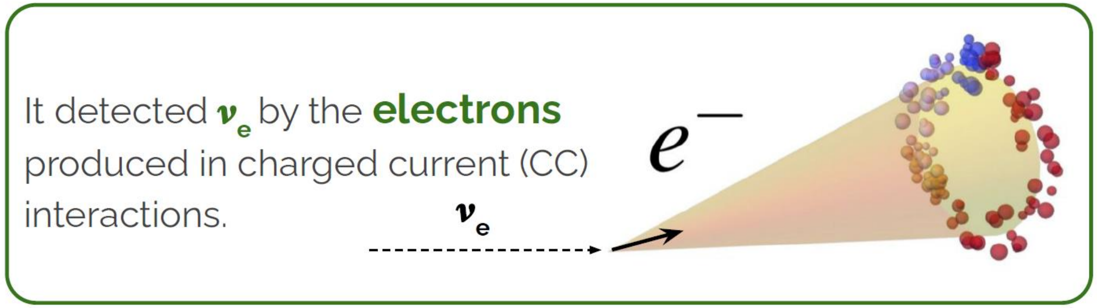


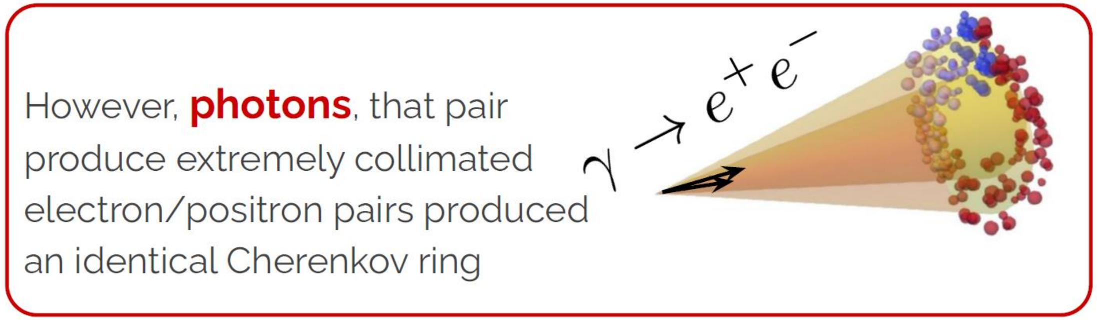
Phys. Rev. D104 (2021) 032003

MiniBooNE Anomaly: Low Energy Excess (LEE)

Phys. Rev. D 103, 052002 (2021)





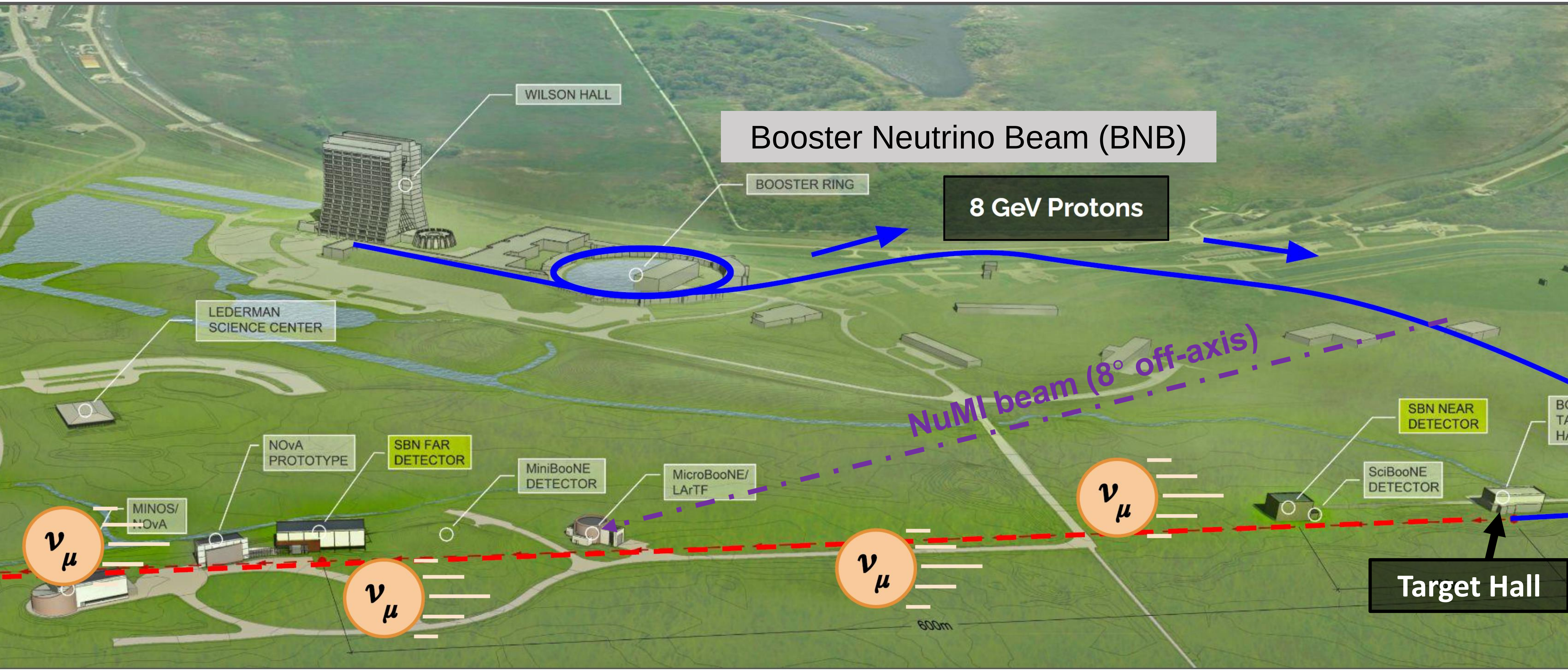


MiniBooNE (2002-2019) observed a low energy excess (LEE) of electromagnetic events with 4.8σ significance.

MiniBooNE Cherenkov detector unable to distinguish photons and electrons, and unable to detect hadronic final-state particles below Cherenkov threshold.

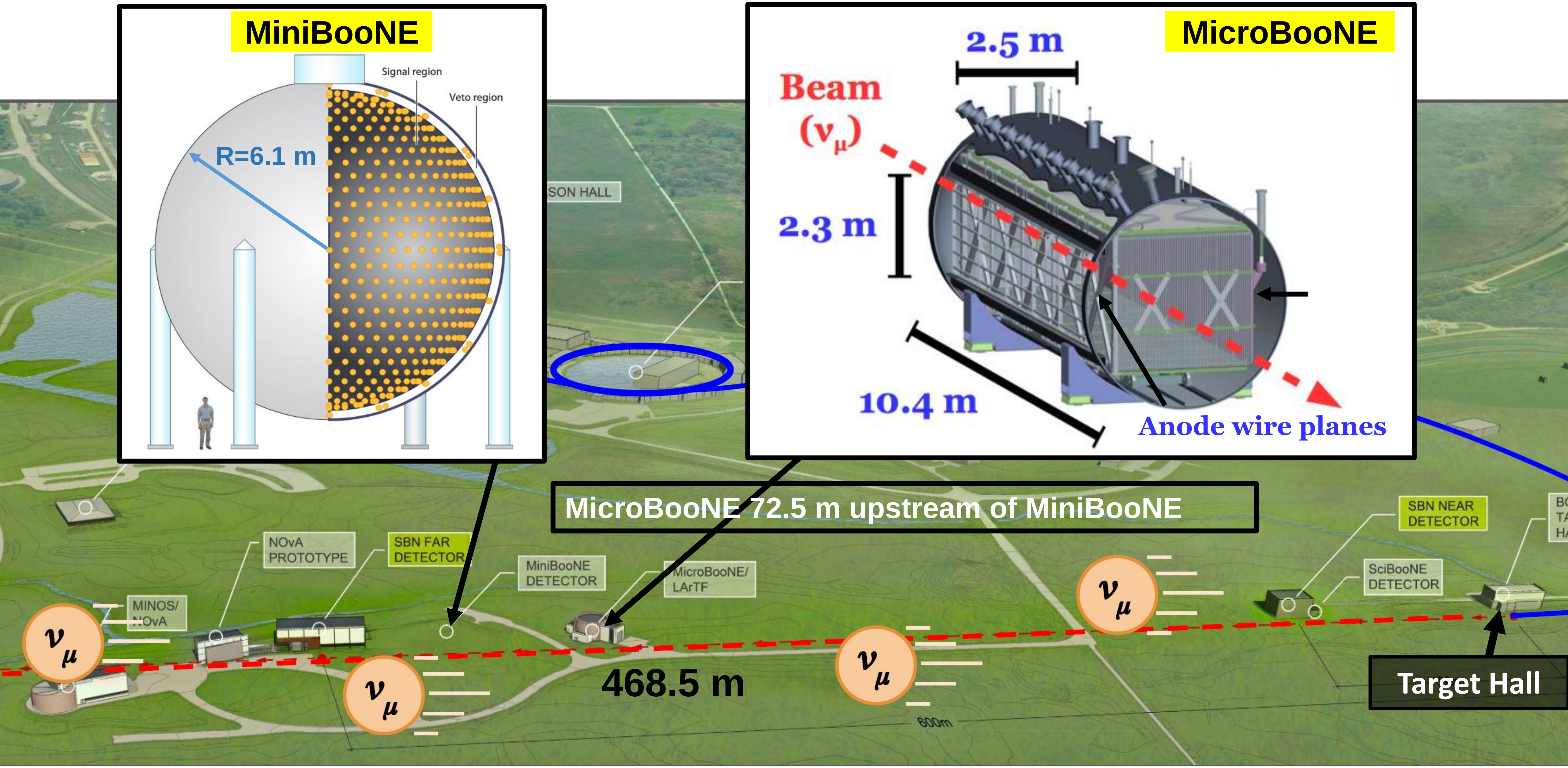
the Micro Booster Neutrino Experiment (MicroBooNE)

MicroBooNE @ Fermilab

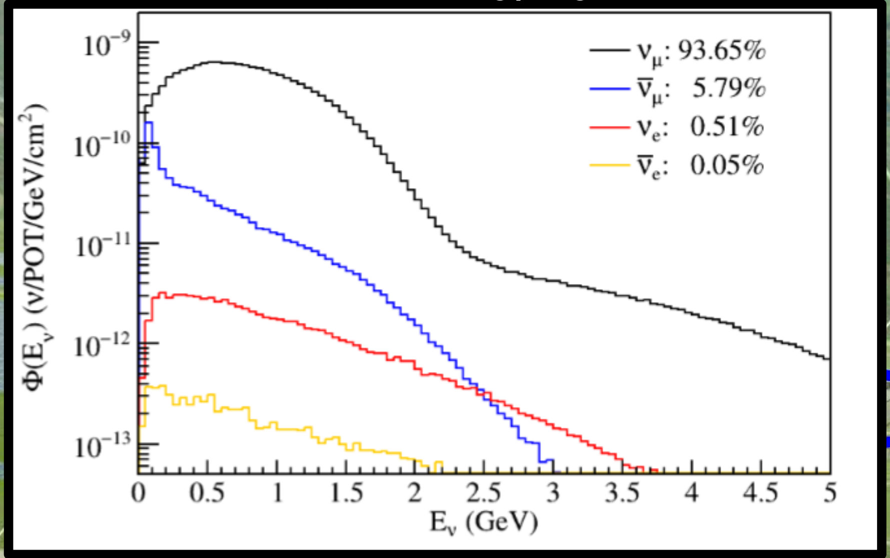


Cherenkov detector: 820 ton mineral oil

170 (85) ton liquid argon in cryostat (TPC) volume



BNB @ MicroBooNE
Mean Neutrino Energy 0.8 GeV.
99.44% $\nu_\mu/\bar{\nu}_\mu$
0.56% $\nu_e/\bar{\nu}_e$



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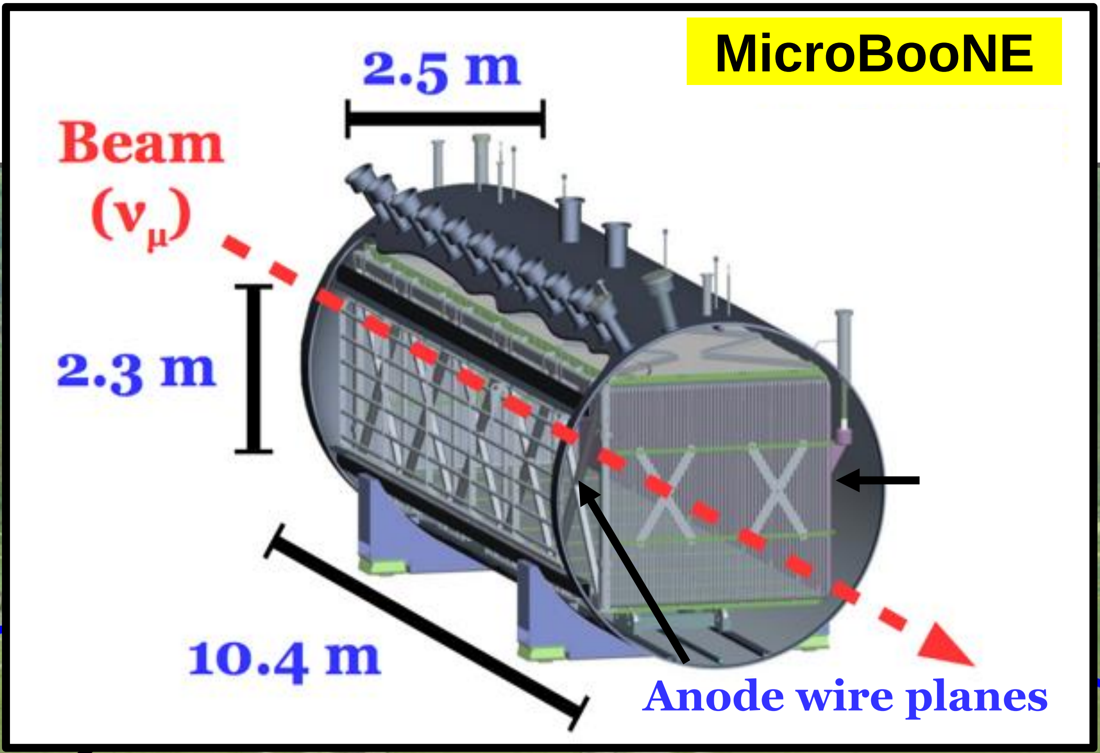
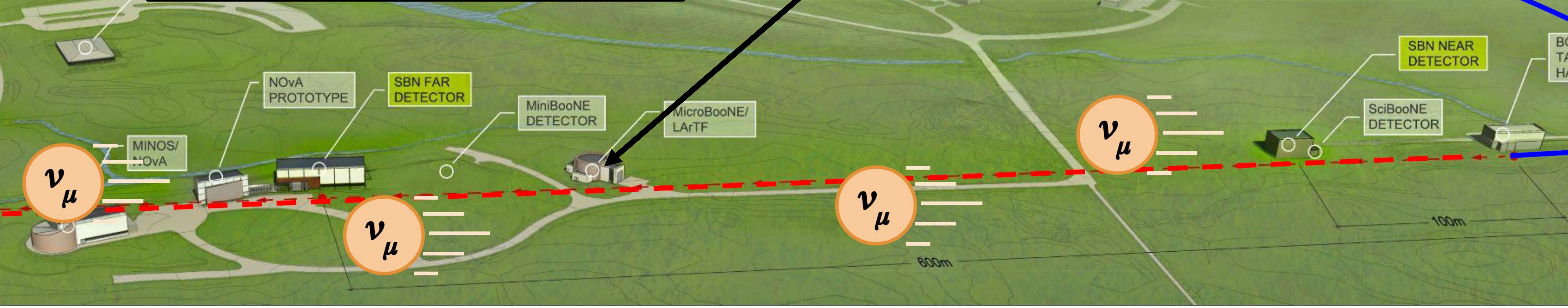


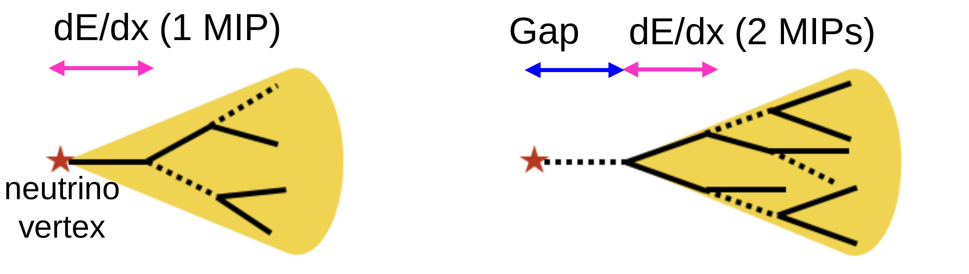


Liquid Argon Time Projection Chamber (LArTPC)

Capable of identifying different species of particles and reconstructing 3D images with fine-grained information

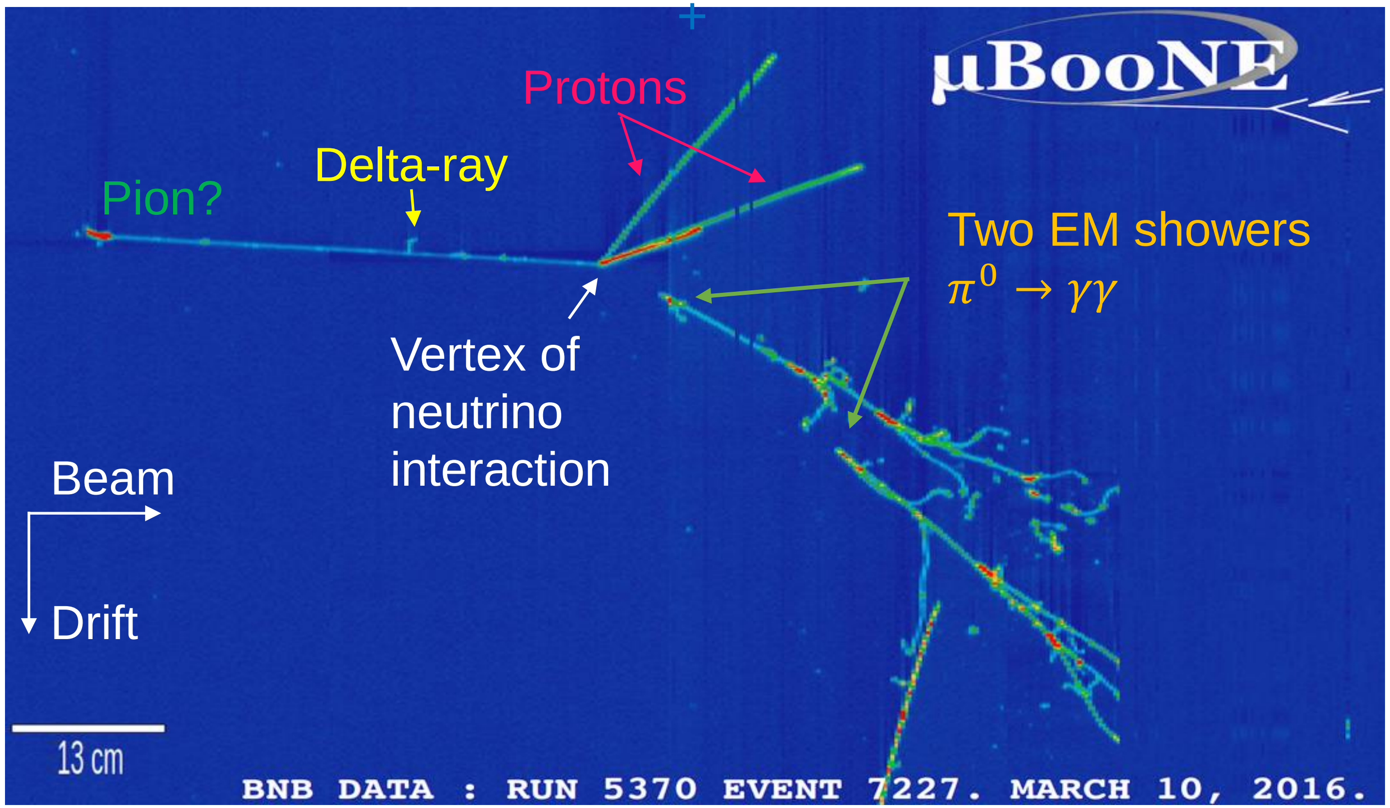
- Neutrino vertex
- Particle flow (mother-daughter relationship)
- Track (μ, π, p etc.) vs shower (e, γ EM cascade)

- **e vs γ (e^+e^- pair production) separation**
  - Gap between shower start point and neutrino vertex?
  - dE/dx in shower stem (1 MIP vs 2 MIPs)



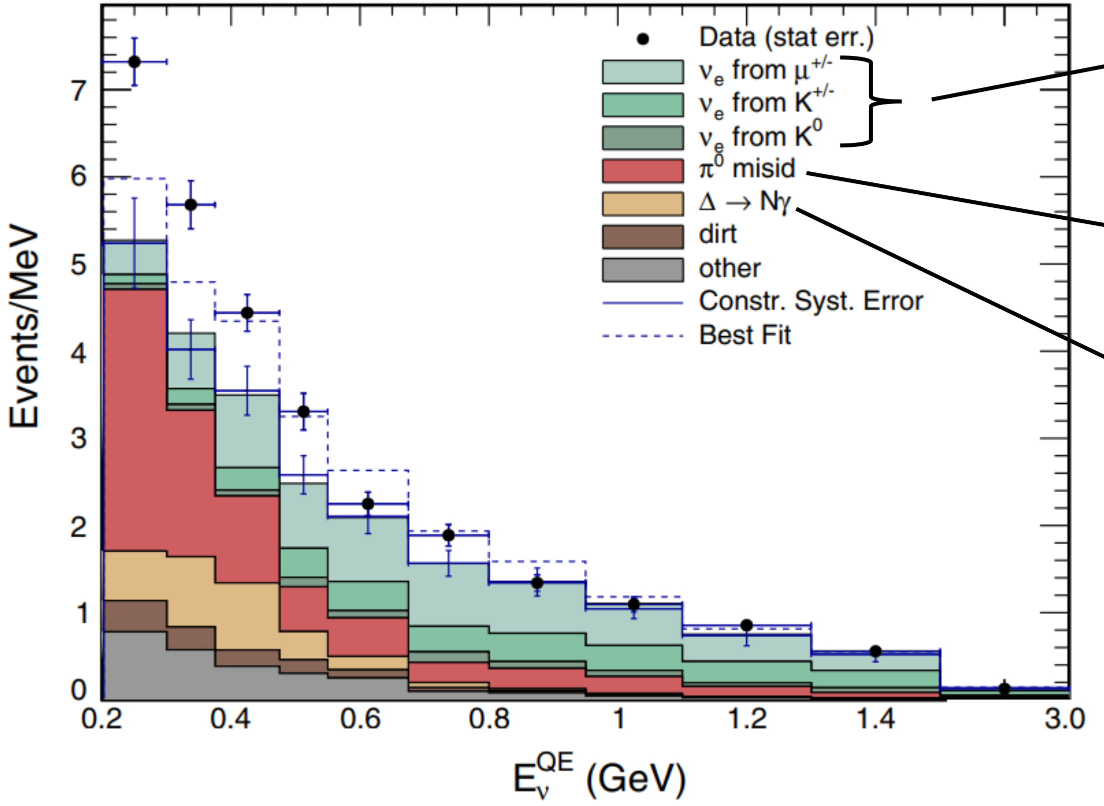
electron shower $\gamma \rightarrow e^+e^-$ shower

LArTPC: high-resolution tracking + fully active calorimeter



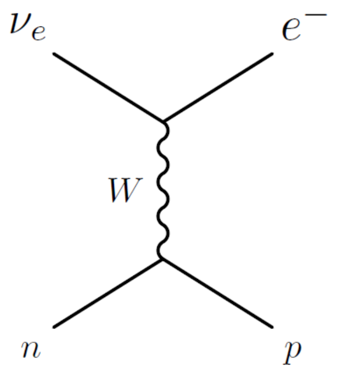
Examine of MiniBooNE LEE

[Phys. Rev. D 103, 052002 (2021)]

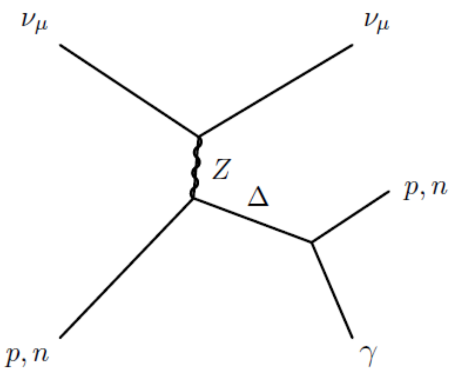


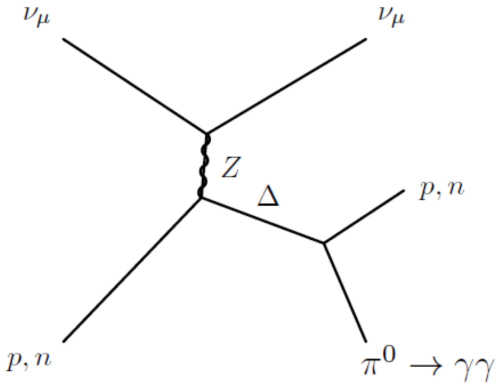
This talk

Irreducible backgrounds. These are electron neutrinos from the beam (beam intrinsic ν_e)



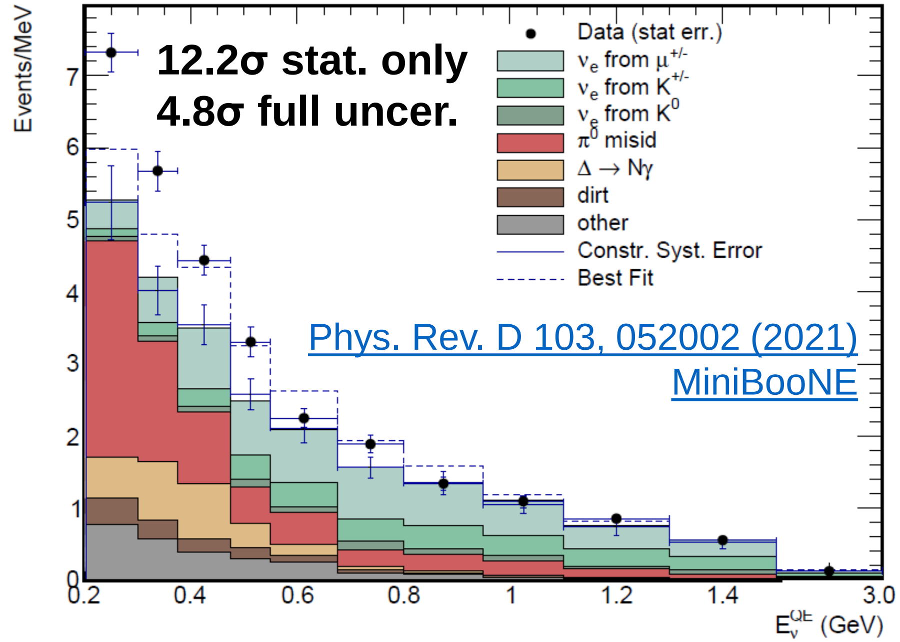
Single-gamma backgrounds

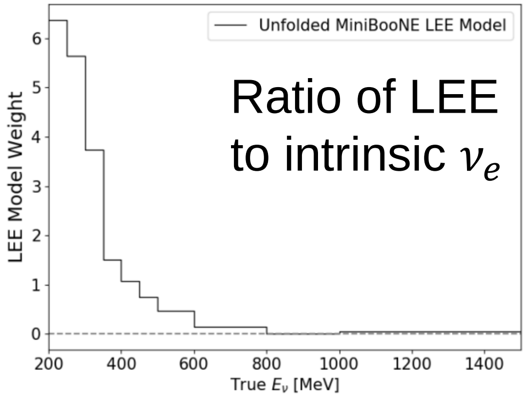


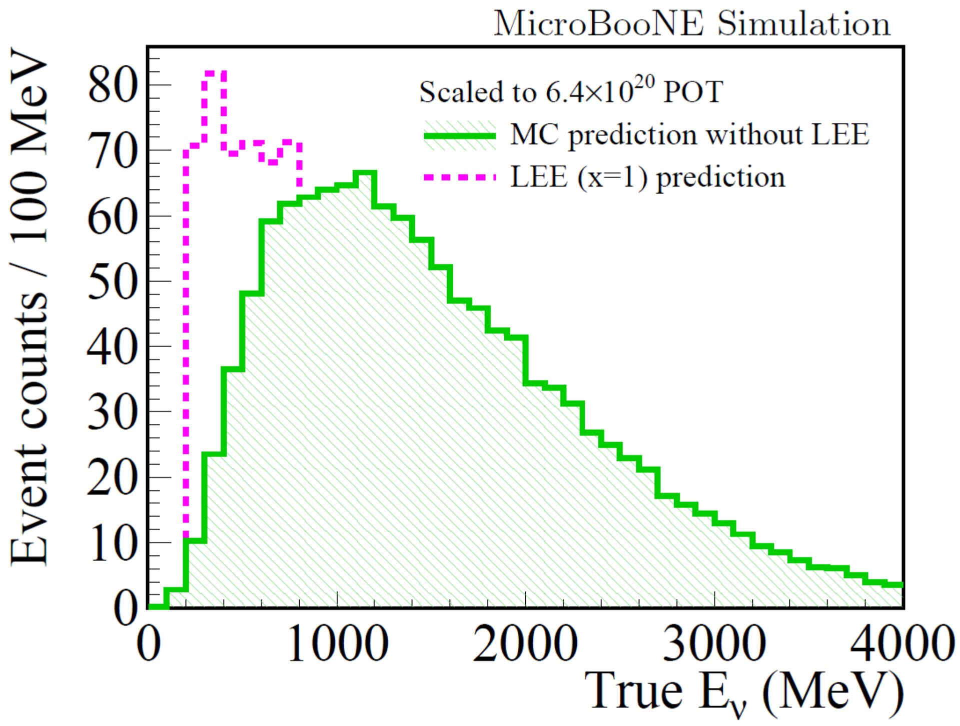


Or other unknown process?

Model of eLEE for the search in MicroBooNE (electron Low Energy Excess)





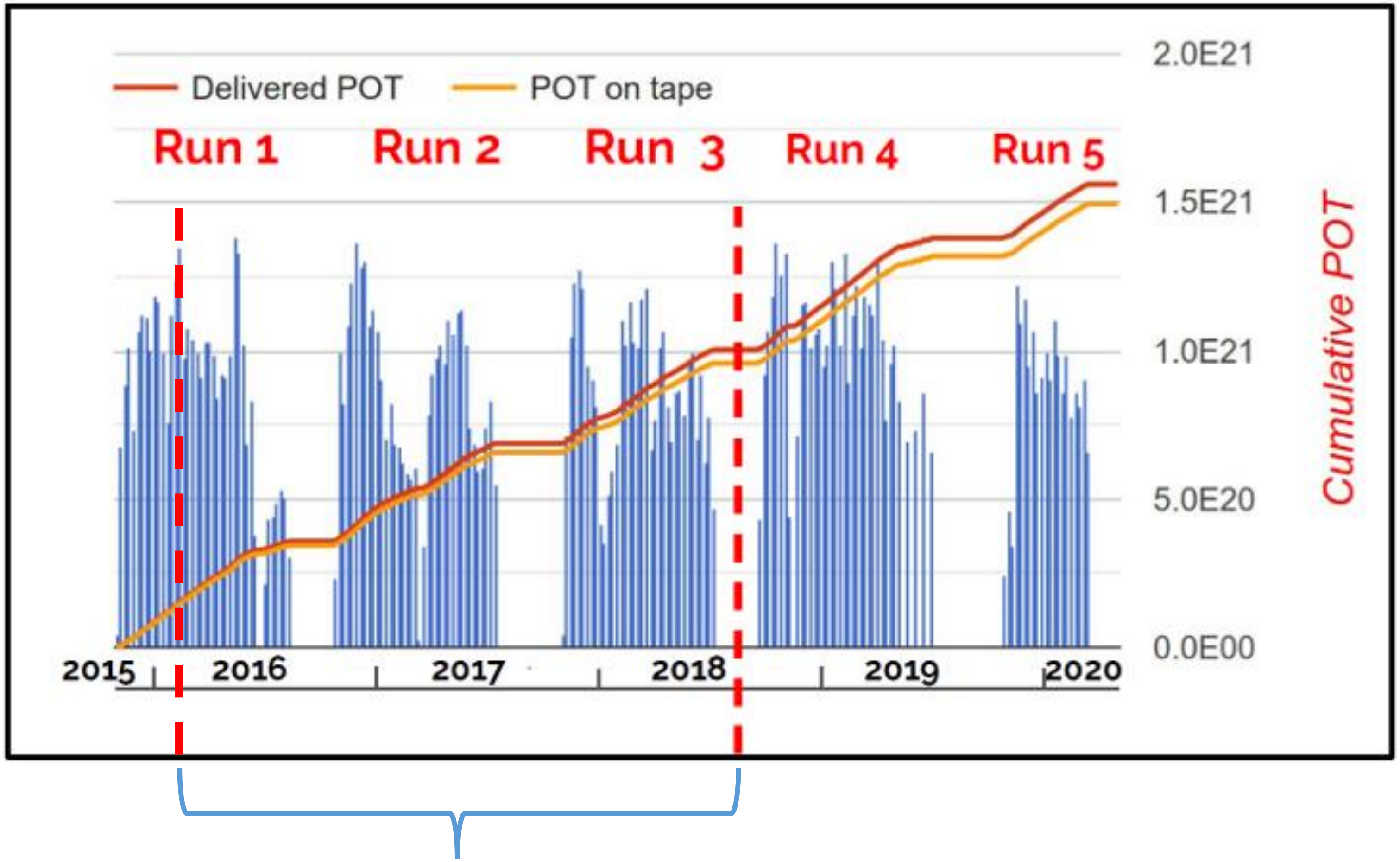


- eLEE is built upon the intrinsic ν_e as a function of neutrino energy
  - Unfolded from MiniBooNE observation and applied to MicroBooNE

- One normalization parameter 'x' built in the model

$$\text{MiniBooNE } x = \begin{cases} 1 \pm 0.08 \text{ (stat.)} \\ 1 \pm 0.21 \text{ (full)} \end{cases}$$

Since turning on in 2015, MicroBooNE has amassed the <u>largest sample of neutrino interactions on argon in the world</u>



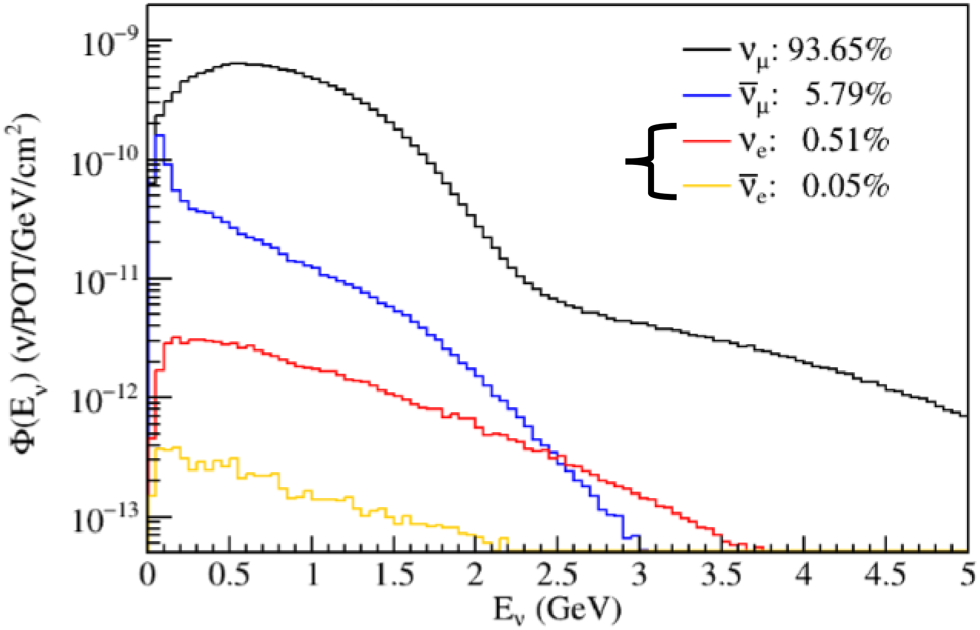
In this talk, I will present results based on $\sim 7 \times 10^{20}$ protons on target (POT) from Run 1-3.

Challenging ν_e Selection

Cosmic-ray muon (5.5 kHz) @ MicroBooNE operating near-surface

- BNB beam spill triggers a 4.8 ms TPC window
- ~600 beam spills → 1 nu interaction

BNB neutrino flux
~0.5% ν_e/anti- ν_e,
over 99% ν_μ /anti- ν_μ



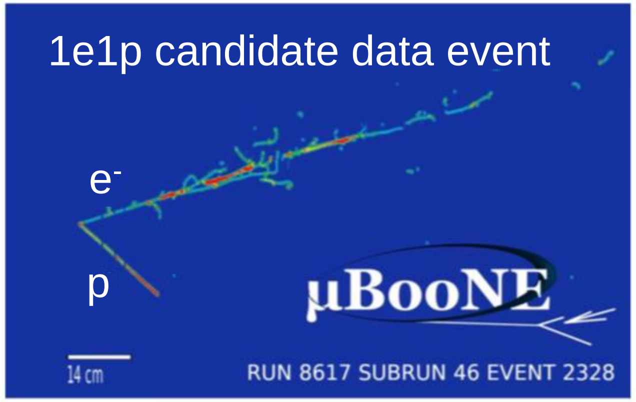
An eLEE-sensitive ν_e selection (CC interactions) requires **≳99.999% rejection of cosmic-ray muons and ≳99.9% rejection of other ν background**

Developed advanced cosmic rejection techniques, event reconstruction and PID algorithms to exploit LArTPC capability to select ν_e events

Three independent eLEE searches

Targeting different final states with different novel reconstruction approaches developed in MicroBooNE

- Restricting to quasi-elastic kinematics: 1e1p,
  Deep-learning-based reconstruction
  Phys. Rev. D105, 112003 (2022)
- MiniBooNE like-final state: 1eNp0π and 1e0p0π,
  Pandora-based reconstruction
- All ν_e final states: 1eX,
  Wire-Cell reconstruction



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  [Phys. Rev. D105, 112004 (2022)](https://doi.org/10.1103/PhysRevD.105.112004)
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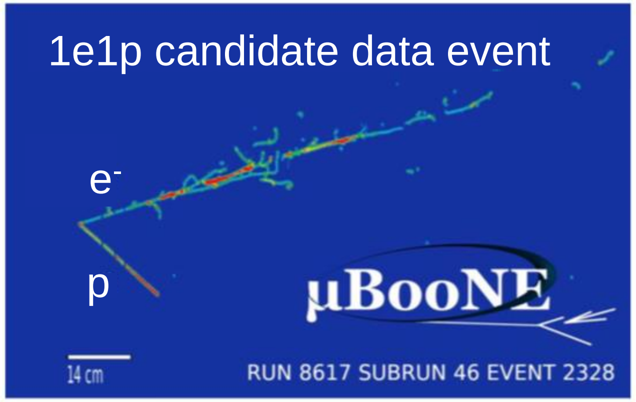

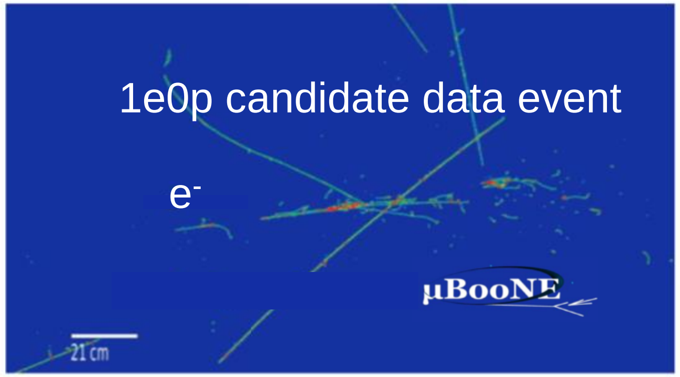

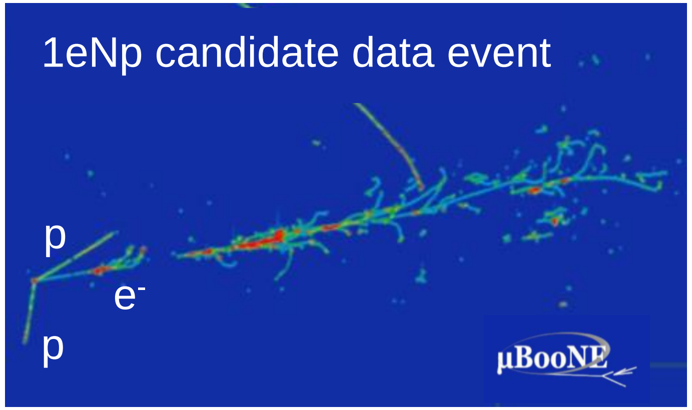

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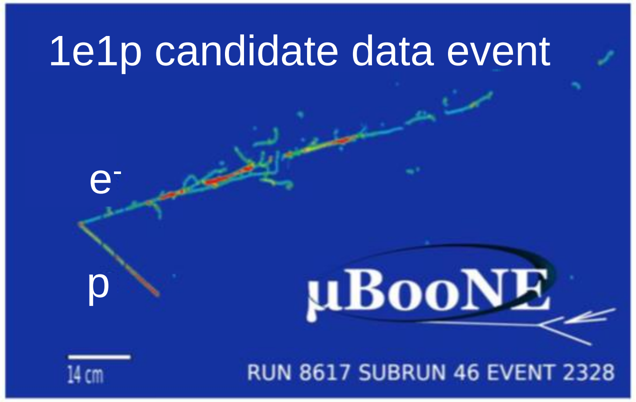
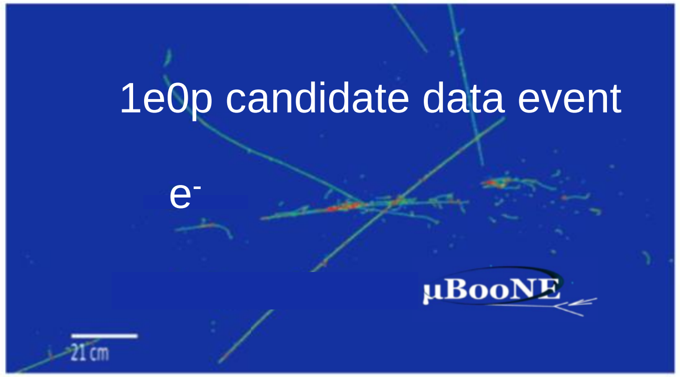
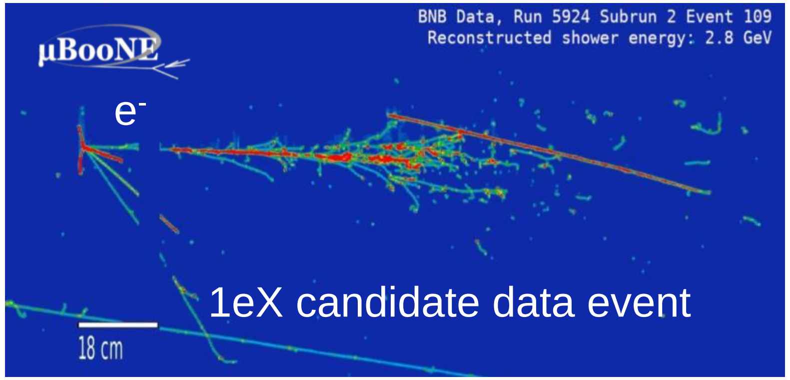
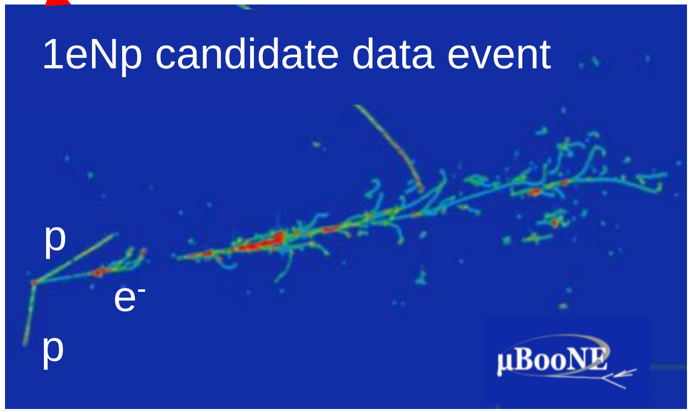
  Phys. Rev. D105, 112005 (2022)



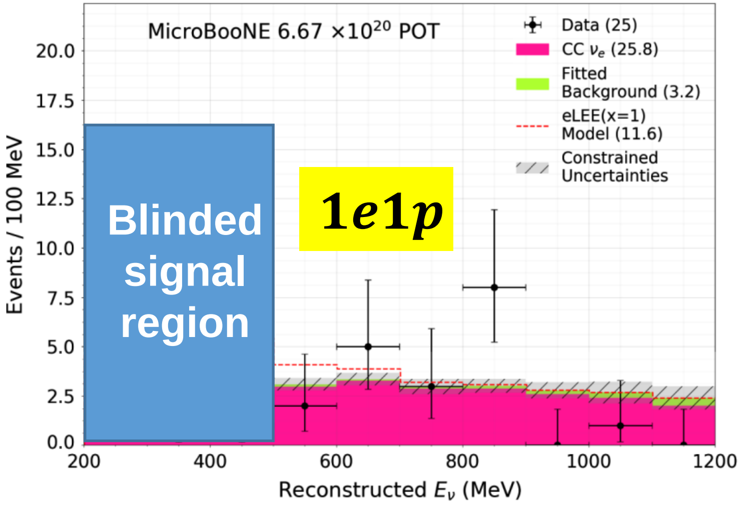


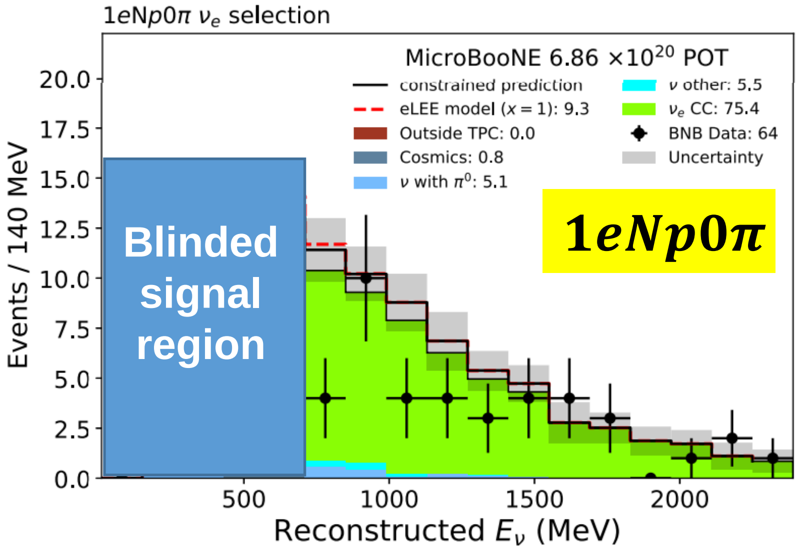


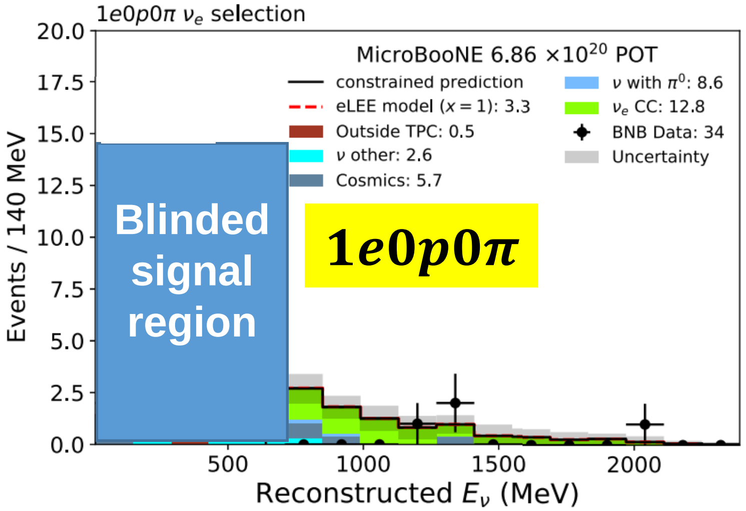


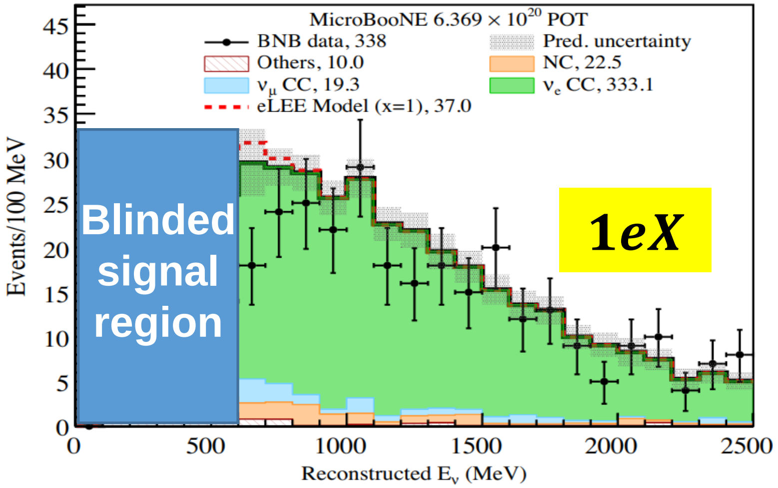
General Analysis Procedure

- Blind analysis (topological characteristics + kinematics sideband)
- NuMI neutrino-beam data validation
- Mock data study



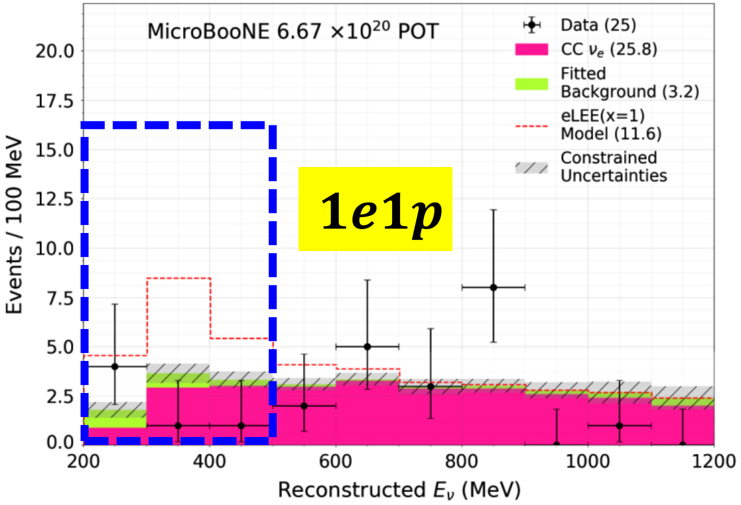


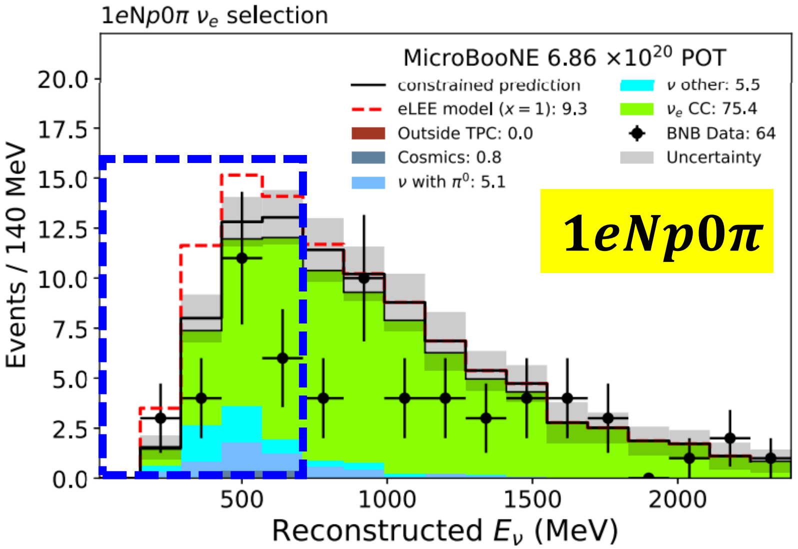


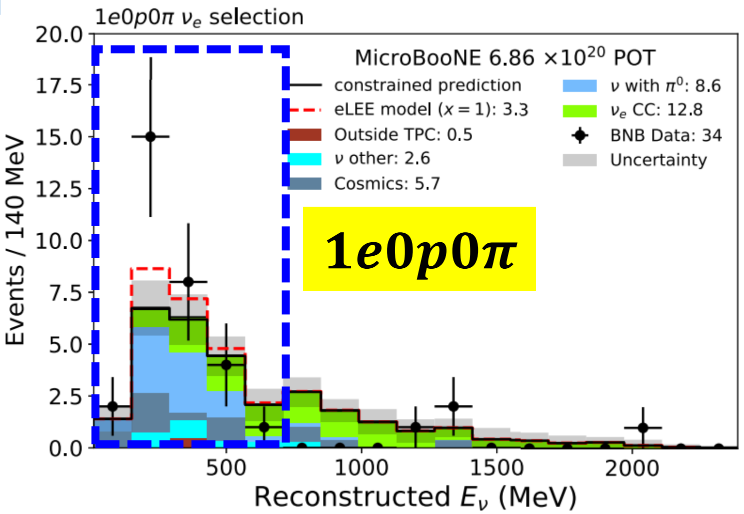


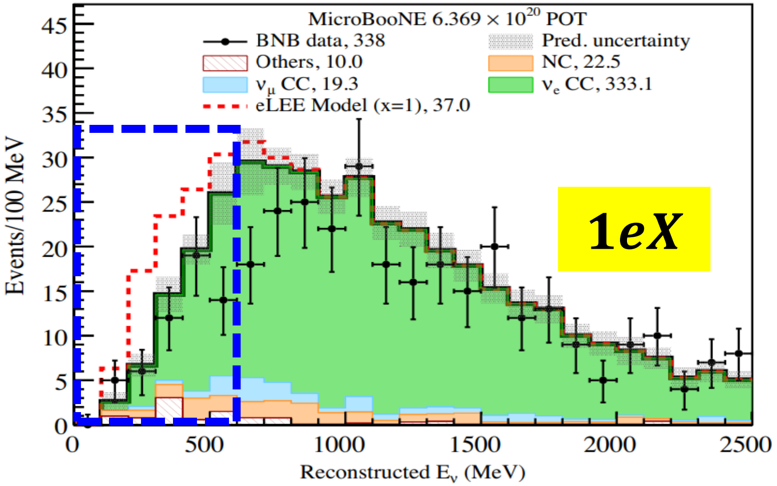
Unblinded Results

- Unblinded in summer 2021
- No observation of ν_e candidate excess in low energy region, except for the low-ν_e-purity ($1e0p0\pi$) channel









[Phys. Rev. D105, 112003 (2022)]
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[Phys. Rev. Lett. 128, 241801 (2022)]

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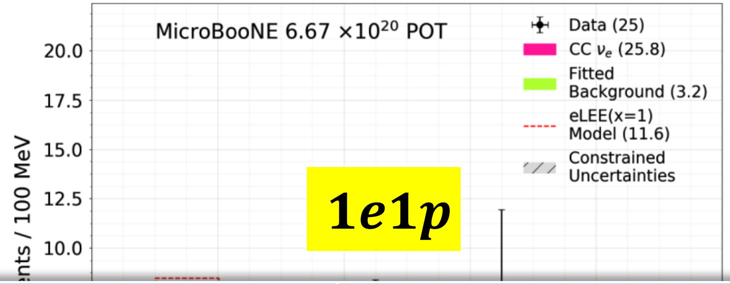

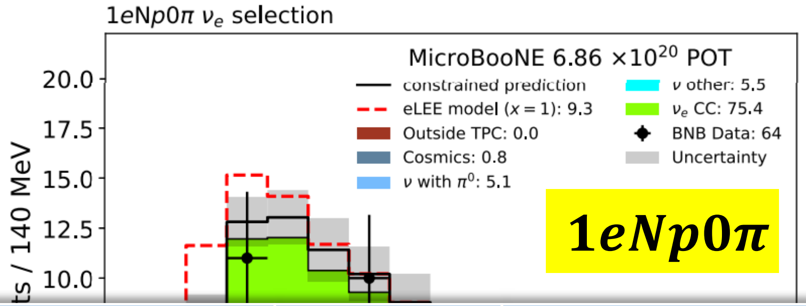

Channels	Reconstruction	Efficiency	Purity	Data Events
CCQE 1e1p	Deep Learning	6.6%	75%	25
1e0p0π	Pandora	9%	43%	34
1eNp0π	Pandora	15%	80%	64
Inclusive 1eX	Wire-Cell	46%	82%	606

Phys. Rev. D105, 112003 (2022)
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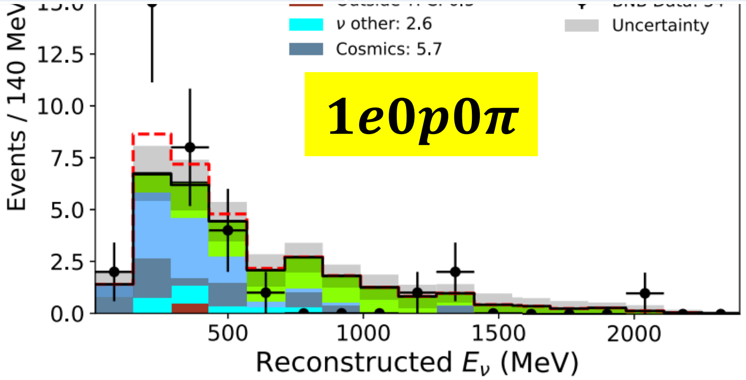
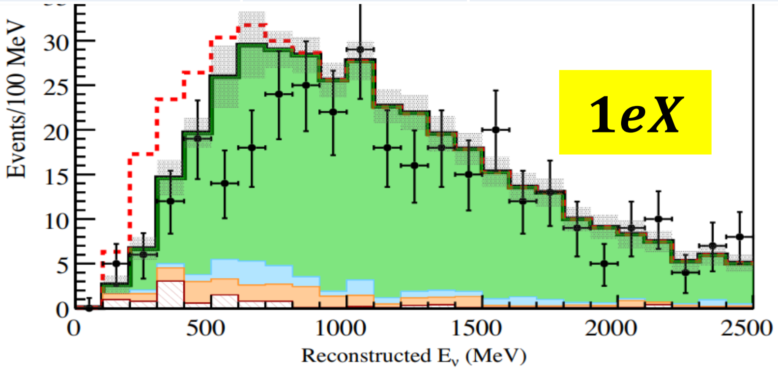
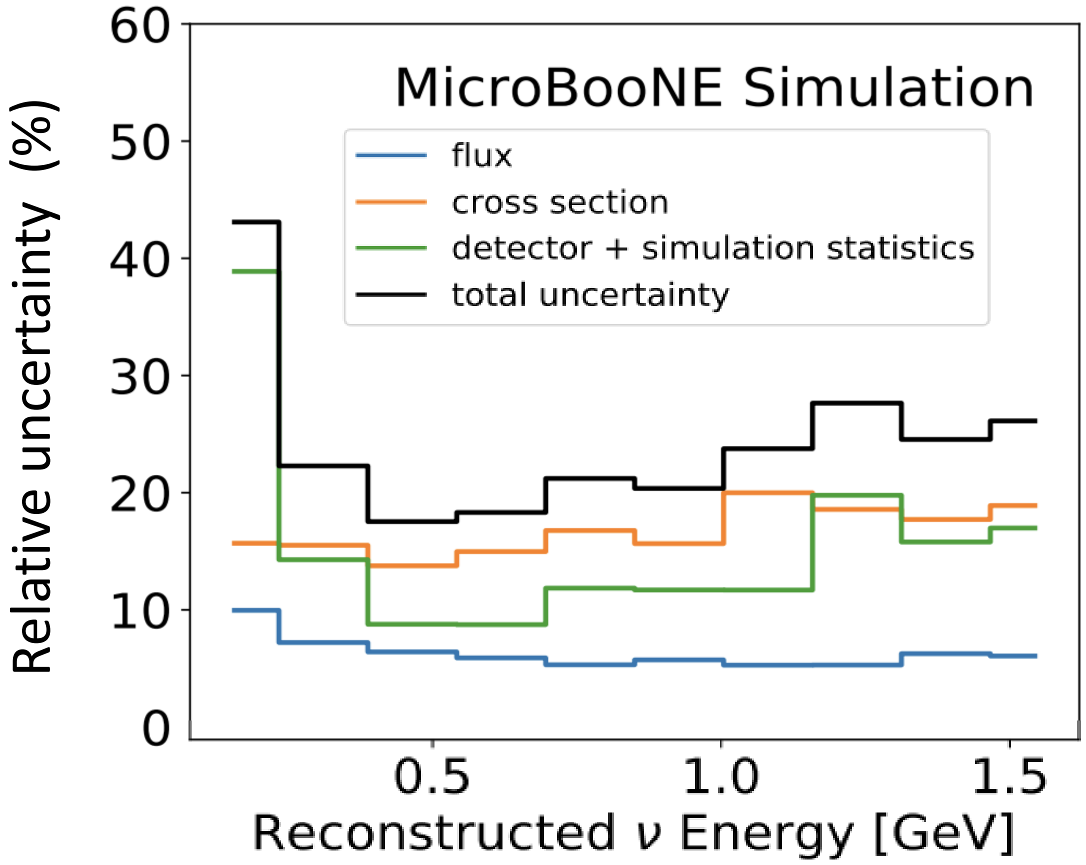




Overview of the Systematic Uncertainties



15-20% cross-section uncertainty

10-20% detector response uncertainty

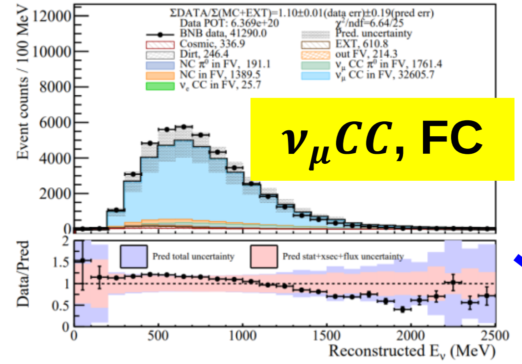
5-10% flux uncertainty (same treatment as MiniBooNE)

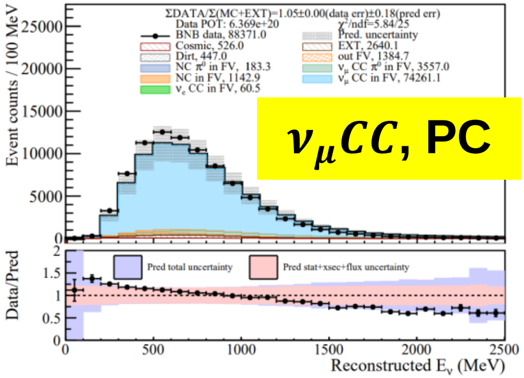
- ➢ Apply data constraints from the in-situ measurements of ν_μ and other dedicated background sidebands to suppress the systematic uncertainties

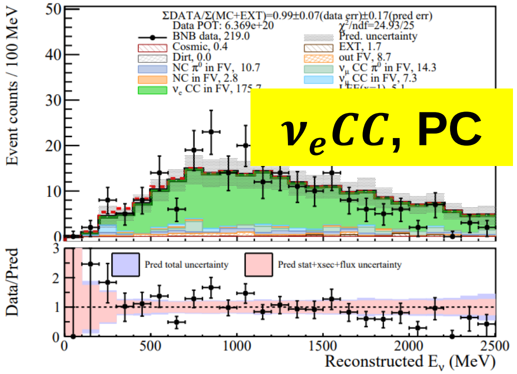
- ✓ Cross-section: MicroBooNE Genie tune, Phys. Rev. D 105, 072001
- ✓ Detector systematics: data-driven, EPJC 82, 454 (2022)

Inclusive 1eX analysis: Phys. Rev. D105, 112005 (2022)

similar constraint procedure used in other two analyses

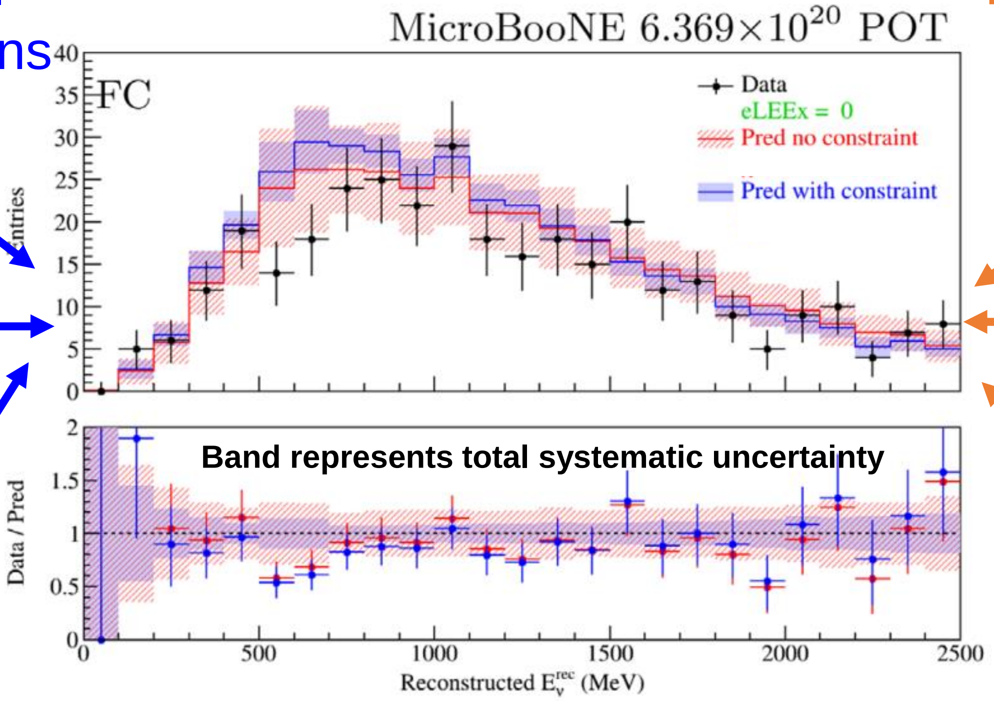




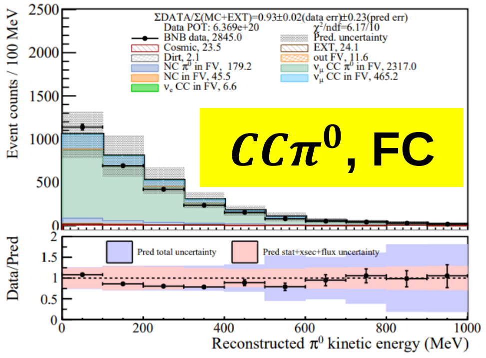


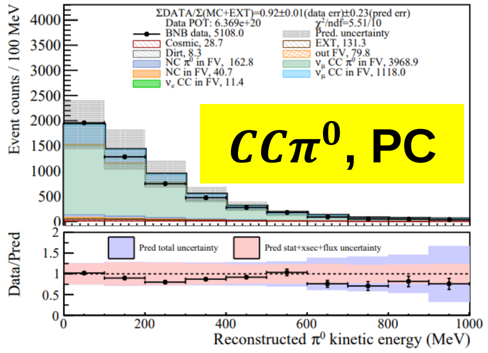
Signal constrains

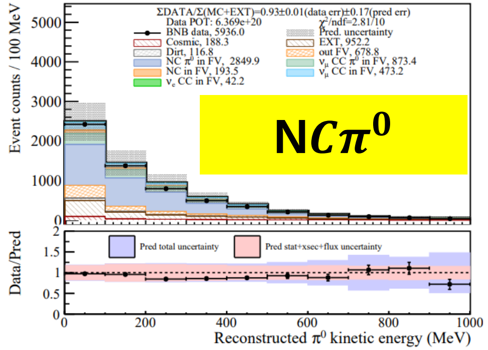
$\nu_e CC$, FC



Background constrains



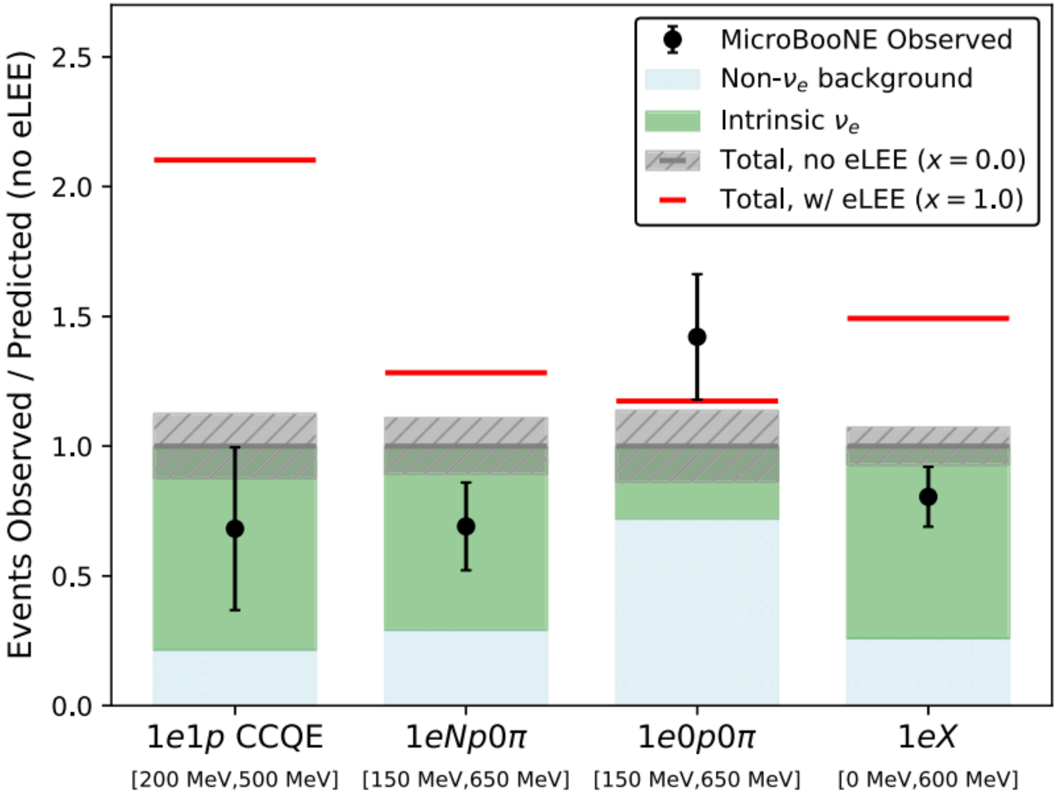




- *FC: fully contained events in the fiducial volume*
- *PC: partially contained events in the fiducial volume*

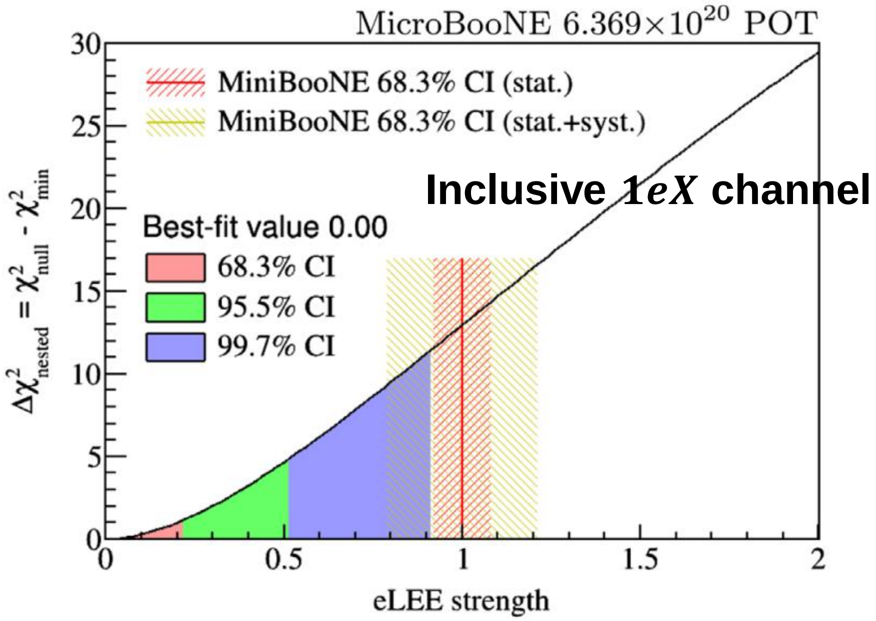
After constraints, the total systematic uncertainty is reduced by **a factor of 3.**

eLEE Search Results

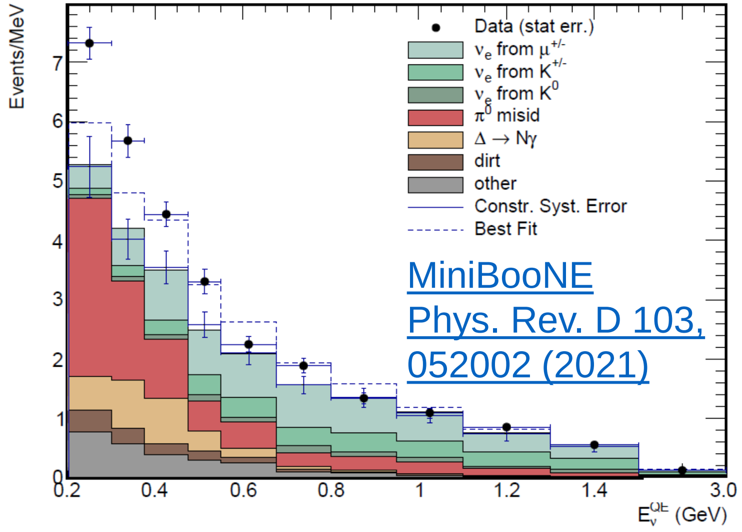


[Phys. Rev. D105, 112003 (2022)](#)
[Phys. Rev. D105, 112004 (2022)](#)
[Phys. Rev. D105, 112005 (2022)](#)
[Phys. Rev. Lett. 128, 241801 (2022)](#)

- Observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region
- With exception of the low-ν_e-purity ($1e0p0\pi$) channel, the hypothesis that ν_e events are fully responsible for the median MiniBooNE LEE is rejected at > 97% C.L.; > 3σ in the inclusive $1eX$ channel



MiniBooNE Excess and Sterile Neutrinos

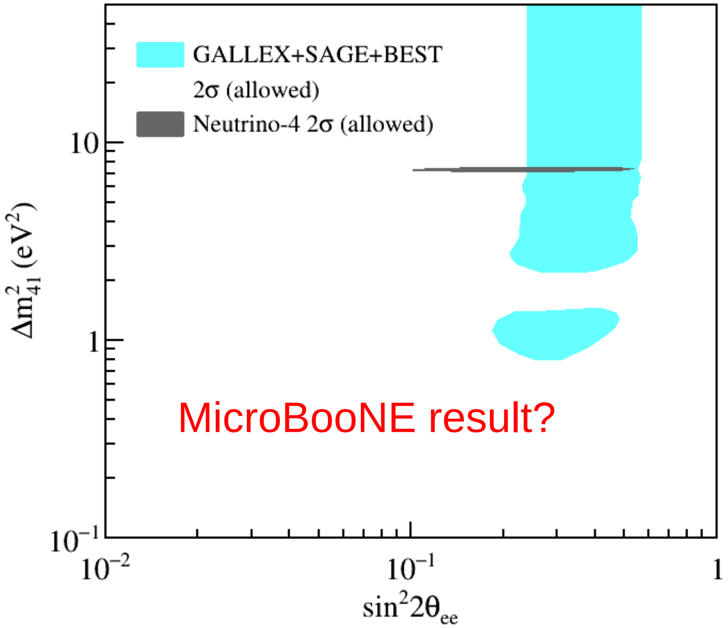


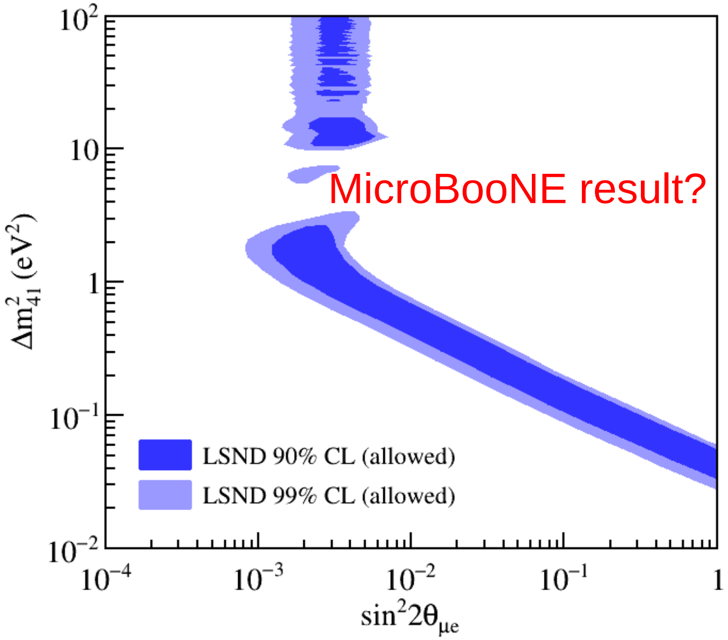
[MiniBooNE Phys. Rev. D 103, 052002 (2021)]

- The MicroBooNE eLEE result disfavors the MiniBooNE anomaly originating from a pure ν_e excess.
- The existence of sterile neutrinos cannot be ruled out by the MicroBooNE eLEE result which is a generic low energy ν_e excess search.

The MicroBooNE eLEE results can be reinterpreted under a sterile neutrino oscillation hypothesis:

a combination of short-baseline ν_e appearance and disappearance





3+1 Neutrino Oscillation Framework

- The PMNS matrix is extended to 4x4 unitary matrix, and is parameterized as following

$$U_{PMNS} = R_{34}(\theta_{34}, \delta_{34})\ R_{24}(\theta_{24}, \delta_{24})\ R_{14}(\theta_{14}, 0)\ R_{23}(\theta_{23}, 0)\ R_{13}(\theta_{13}, \delta_{13})\ R_{12}(\theta_{12}, 0)$$

- The effective mixing angles $\theta_{\alpha\beta}$ for short-baseline oscillations are defined below

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \cdot \sin^2 2\theta_{\alpha\beta} \cdot \sin^2\left(1.267 \frac{\Delta m_{41}^2(\mathrm{eV}^2) L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$

ν_e disappearance ($\nu_e \to \nu_e$): $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

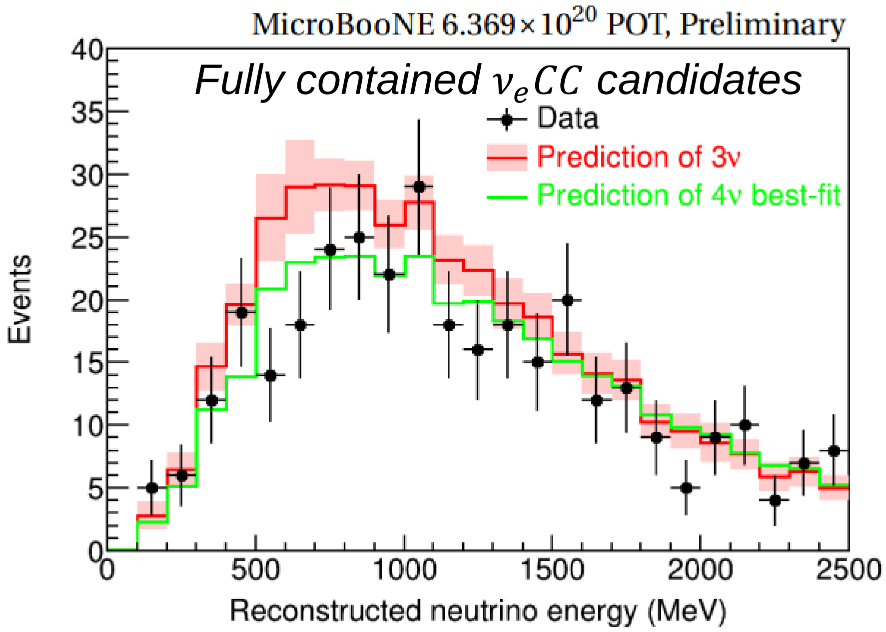
ν_μ disappearance ($\nu_\mu \to \nu_\mu$): $\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}\,(1 - \cos^2\theta_{14}\sin^2\theta_{24})$

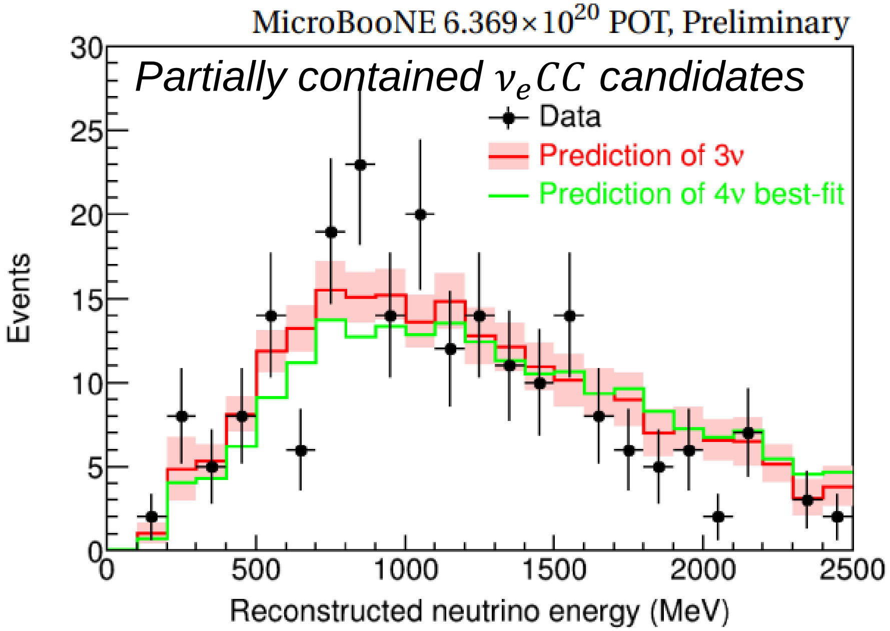
ν_e appearance ($\nu_\mu \to \nu_e$): $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$

- In MicroBooNE analysis, the above three oscillation effects are applied to all ν_e and ν_μ events; the ν_μ appearance ($\nu_e \to \nu_\mu$) is ignored because of tiny $\frac{\nu_e\ \text{flux rate}}{\nu_\mu\ \text{flux rate}} \sim 0.005$

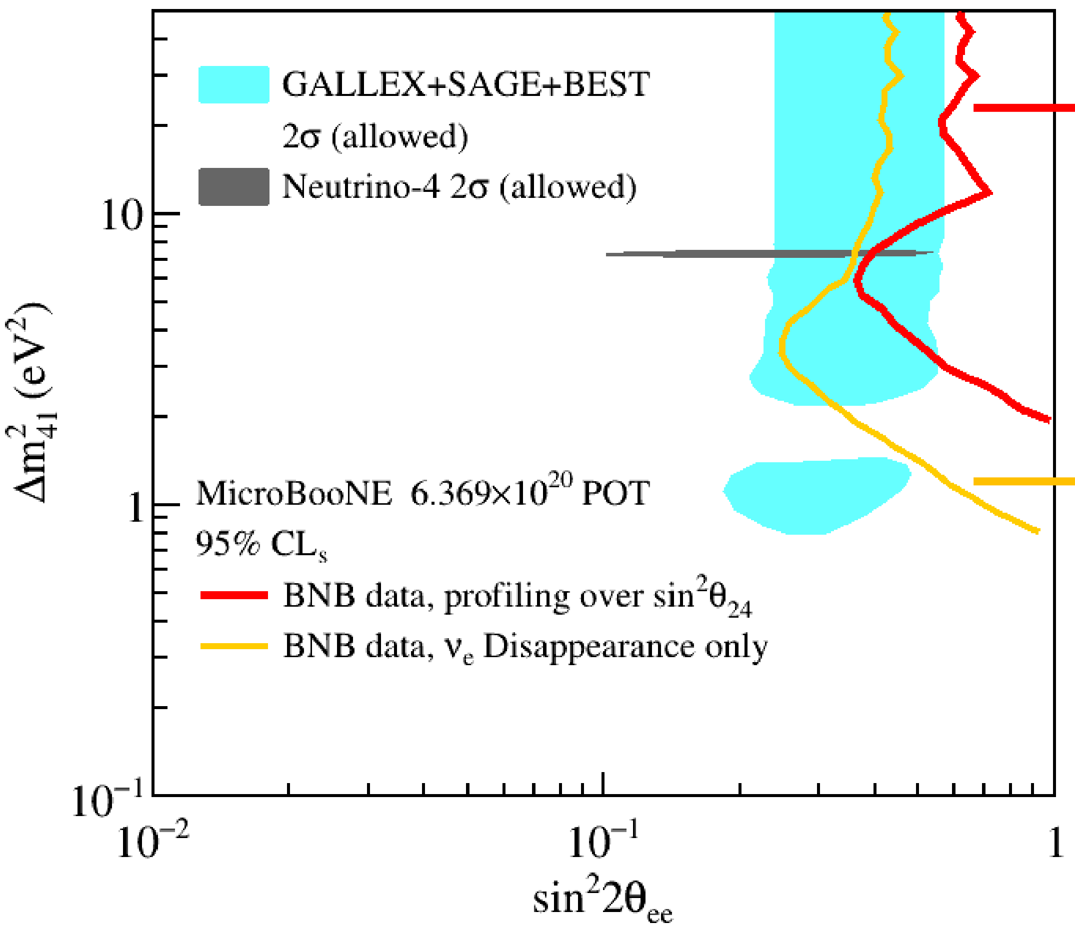
3+1 Oscillation Analysis using Wire-Cell Inclusive Selections

- Three oscillation effects (ν_e appearance, ν_e and ν_μ disappearance) are simultaneously applied on multiple selection channels including $\nu_e\mathrm{CC}$, $\nu_\mu\mathrm{CC}$, and NC (same inputs as the inclusive 1eX eLEE search)
- Considering full 3+1 oscillation, the BNB data result is found to be consistent with the 3ν hypothesis within 1σ following the Feldman-Cousins approach
- 95% C.L. exclusion limits are calculated using the frequentist CLs method





MicroBooNE 3+1 Oscillation Analysis Results: Δm_{41}^2 vs. $\sin^2 2\theta_{ee}$

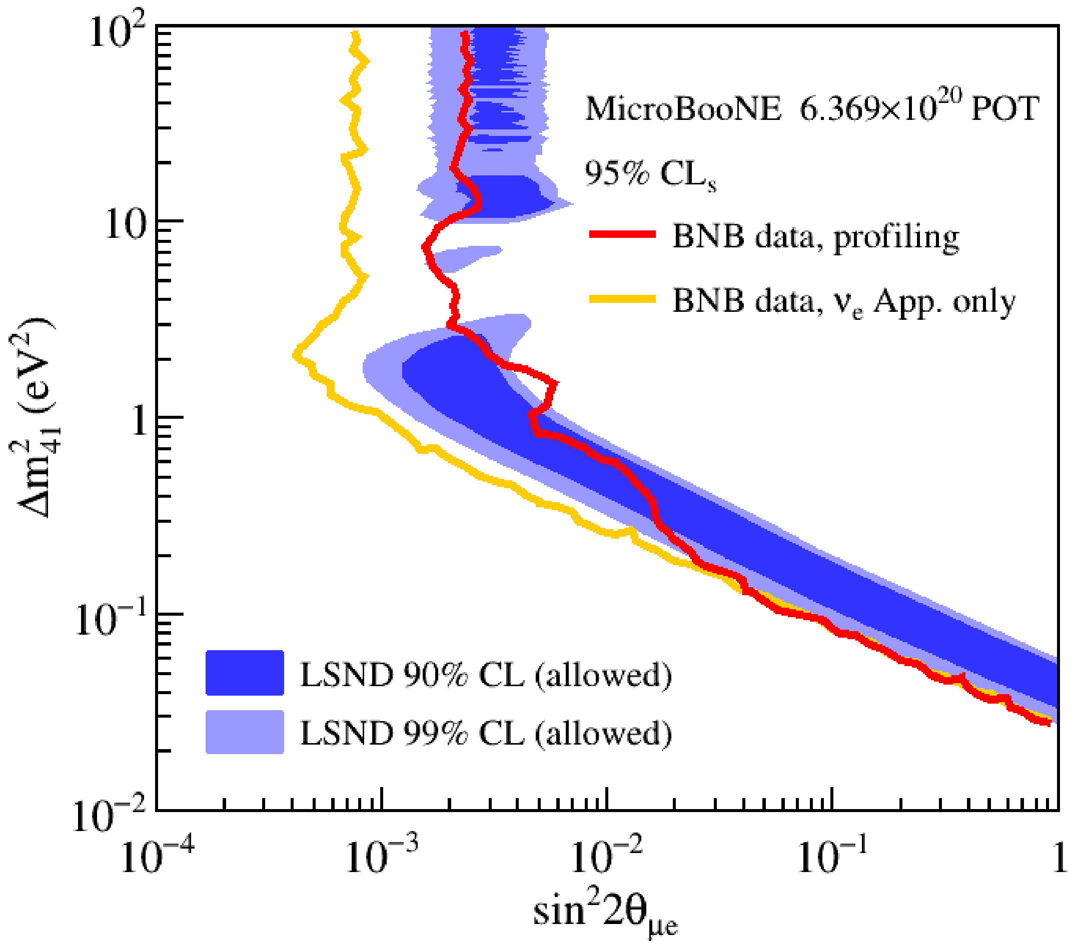


2D profiled result, full 3+1 analysis at each point in the parameter space

ν_e disappearance-only, more stringent limit corresponding to a fixed $\sin^2\theta_{24} = 0$

Competitive limit on the eV-scale ν_e disappearance

MicroBooNE 3+1 Oscillation Analysis Results: Δm^2_{41} vs. $\sin^2 2\theta_{\mu e}$



- Part of the LSND allowed region is excluded by the **MicroBooNE 3+1 analysis** 95% CL limit
- **ν_e appearance-only**, more stringent limit. However, it is physically not allowed in the 3+1 framework. (non-zero ν_e appearance requires both ν_e and ν_μ disappearance)

Cancellation of ν_e Appearance and ν_e Disappearance → Degeneracy of Oscillation Parameters

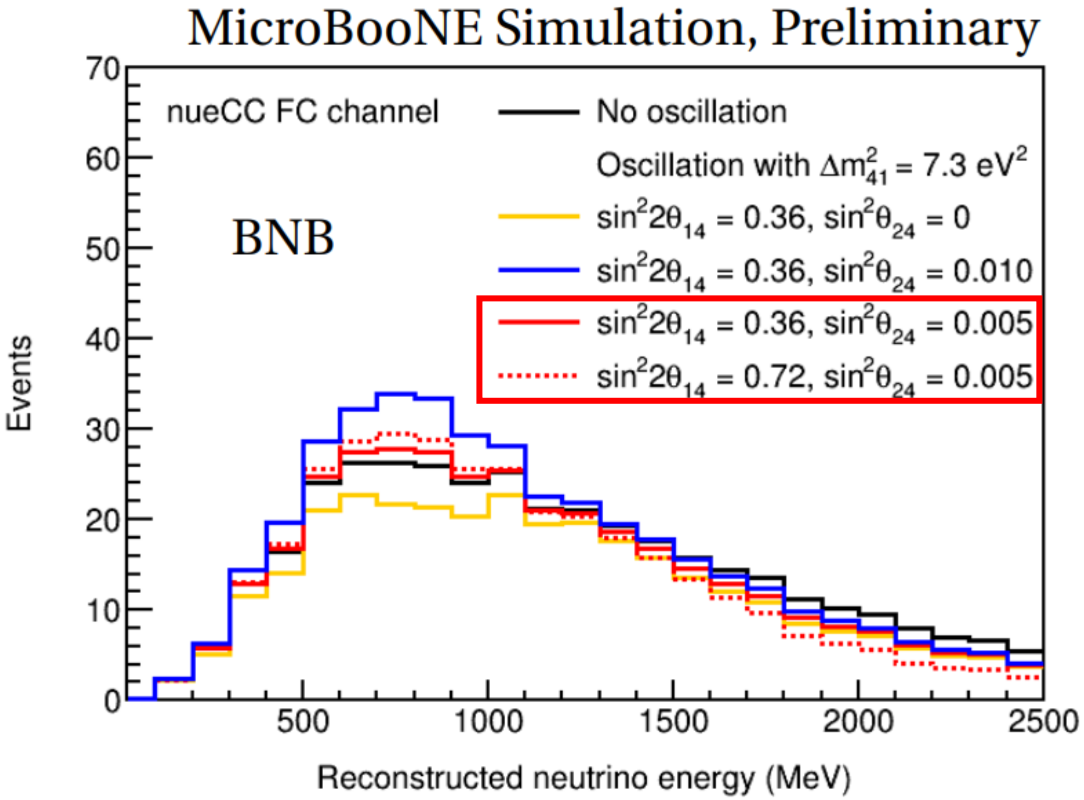
- Observed ν_e events are a combination result of ν_e appearance and disappearance

$$N_{\nu_e} = \boxed{N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e}} + \boxed{N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + \boxed{(R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1)} \cdot \sin^2 2\theta_{14} \cdot \sin^2\Delta_{41}\right]$$

- Degeneracy when $\sin^2\theta_{24}$ approaches R_{ν_e/ν_μ} (the ratio of beam intrinsic ν_e and ν_μ flux)

- Sensitivity/exclusion limits become much worse around the degeneracy point

	R_{ν_e/ν_μ} (degeneracy $\sin^2\theta_{24}$ value)
MicroBooNE w. BNB	~0.005 (average)

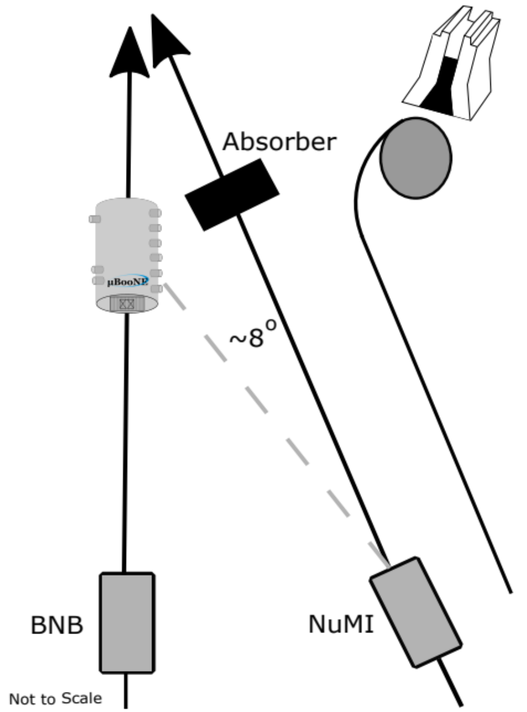


Breaking the Degeneracy

- Observed ν_e events are a combination result of ν_e appearance and disappearance

$$N_{\nu_e} = \boxed{N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e}} + \boxed{N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + \boxed{(R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1)} \cdot \sin^2 2\theta_{14} \cdot \sin^2\Delta_{41}\right]$$

- Degeneracy when $\sin^2\theta_{24}$ approaches R_{ν_e/ν_μ} (the ratio of beam intrinsic ν_e and ν_μ flux)



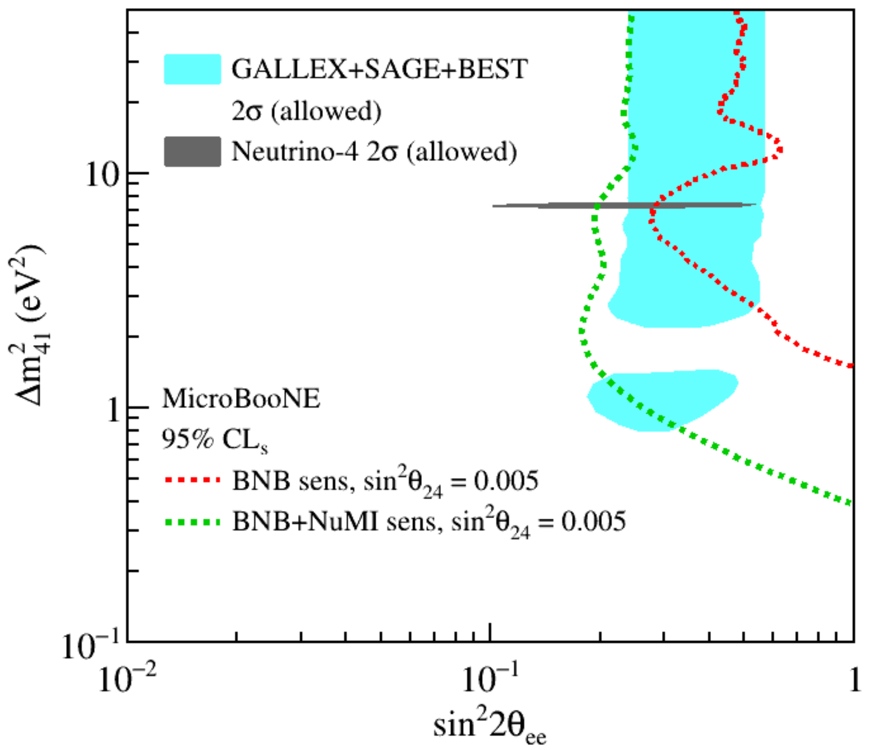
	R_{ν_e/ν_μ} (degeneracy $\sin^2\theta_{24}$ value)
MicroBooNE w. BNB	~0.005 (average)
MicroBooNE w. NuMI	~0.04 (average)

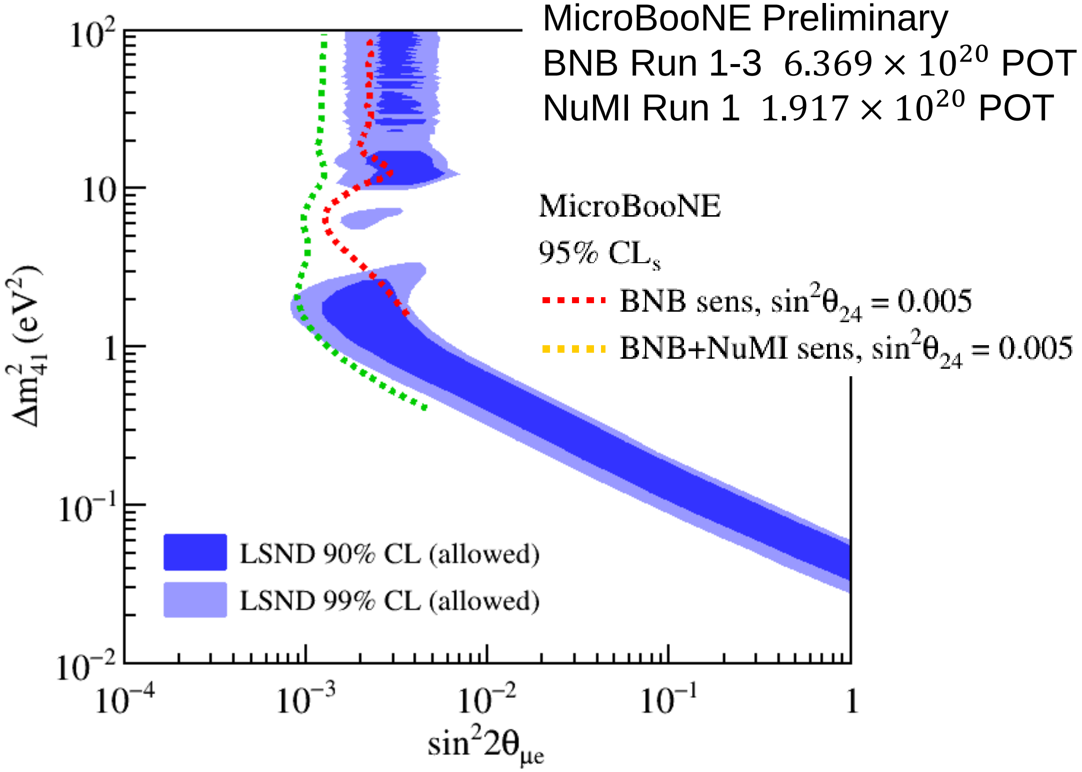
Two neutrino beams at MicroBooNE:

- BNB, on-axis, baseline ~470m
- NuMI, off-axis, baseline ~680m

Significant difference in the numu/nue ratio in BNB and NuMI → mitigate the degeneracy

MicroBooNE 3+1 Oscillation Analysis Sensitivities BNB and BNB+NuMI



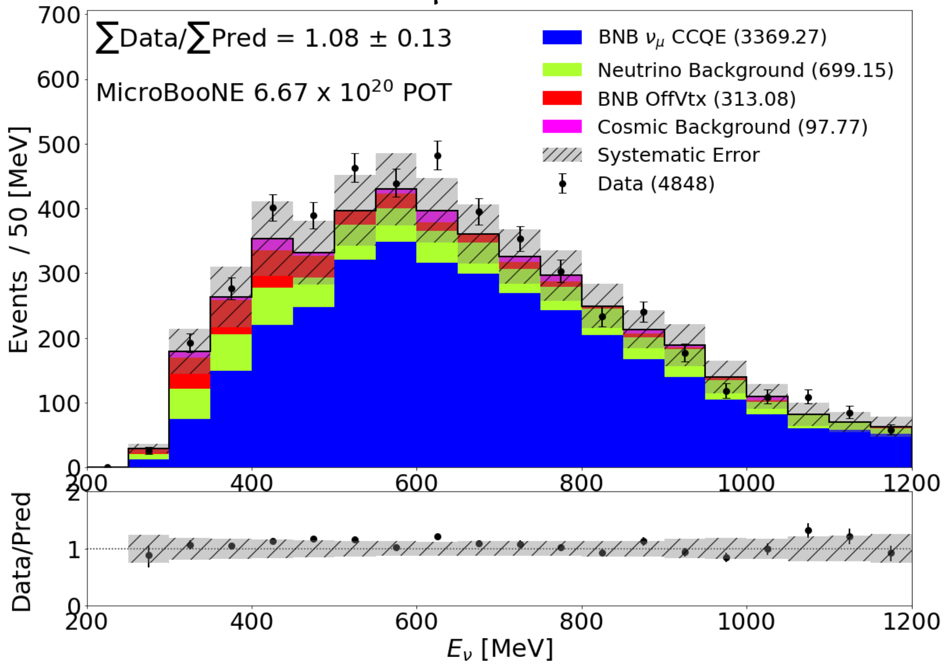


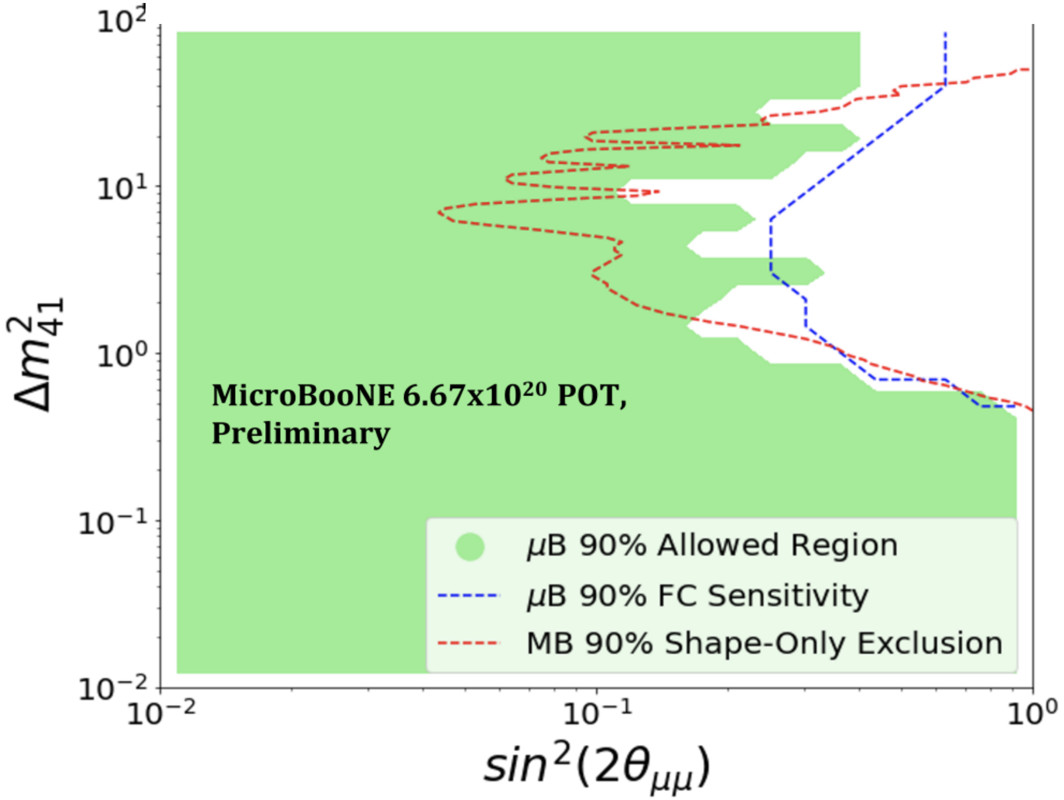
- Sensitivity is significantly improved (overall a factor of 2) when combining both BNB and NuMI (mainly due to **degeneracy mitigation**)
- BNB+NuMI data result is coming soon, expected to be sensitive to the Gallium/Neutrino-4 results, and LSND results

3+1 Oscillation Analysis using Deep-learning-based ν_e/ν_μ Selections

- Uses CCQE-dominated 98% pure ν_μ selection (deep-learning-based 1μ1p selection)
- The BNB data (Run 1-3) was found to be consistent with the 3ν (null) hypothesis
- MicroBooNE's Feldman-Cousins allowed region, compared to our sensitivity, is shown against the MiniBooNE shape-only exclusion limit

1μ1p-like ν_μ CC candidates

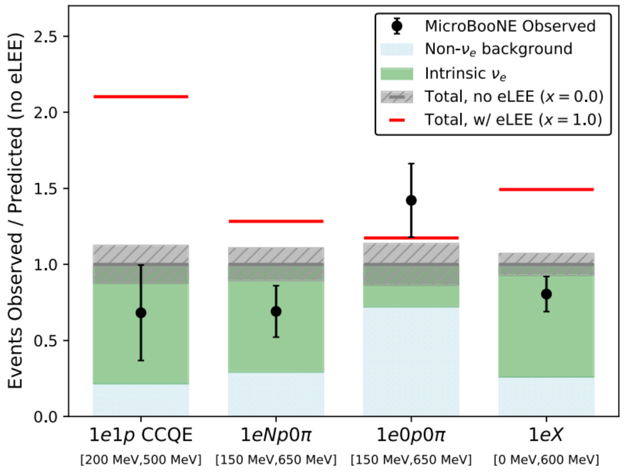


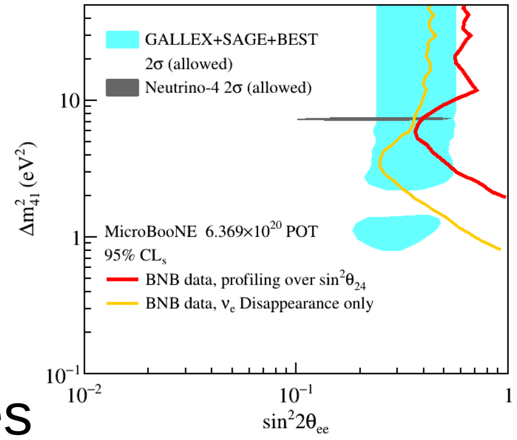


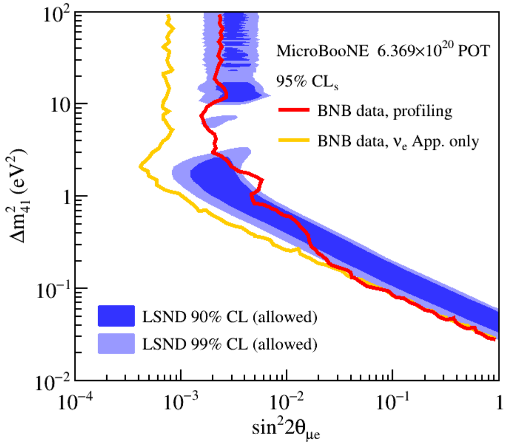
- A full 3+1 analysis using deep-learning-based ν_e and ν_μ selections is coming.

Summary

- MicroBooNE's first searches for low energy excess found no evidence of excessive ν_e to explain the MiniBooNE excess
  - Disfavor pure ν_e excess as a sole source of MiniBooNE excess at 3σ level
- Full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis
  - The data (50% BNB total dataset) was found to be consistent with three-flavor hypothesis and exclusion limits were calculated using a frequentist approach
  - Unitizing both BNB and NuMI data, the 3+1 analysis will be sensitive to Gallium/Neutrino-4 and LSND results
- Further investigation on MiniBooNE excess, searches for photon-like events, other BSM particles/process (e.g. e^+e^-), oscillation analysis are underway







Other MicroBooNE NuFACT 2022 Talks

WG5: Beyond PMNS

- Kathryn Sutton, *MicroBooNE's Search for Anomalous Single-Photon Production in Neutrino Scattering*

WG2: Neutrino Scattering Physics

- Afroditi Papadopoulou, *Recent MicroBooNE cross-section results: neutrino-induced baryon production*
- Elena Gramellini, *Recent MicroBooNE cross-section results: inclusive channels and pion production*
- Marco Martini, *Investigation of the MicroBooNE inclusive neutrino cross sections on Argon*

WG6: Detectors

- Wanwei Wu, *Energy Reconstruction and Calibration of the MicroBooNE LArTPC*

Posters

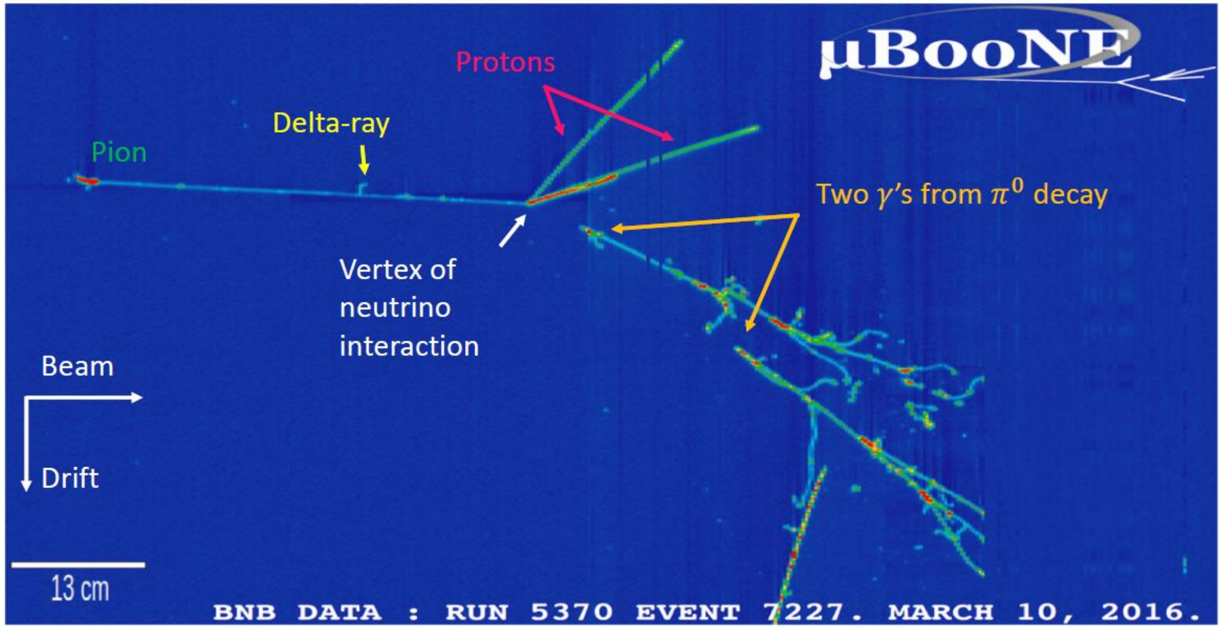
- Christopher Thorpe, *Measurement of the Λ Baryon Production Cross Section in Neutrino Interactions with MicroBooNE*
- Meghna Bhattacharya, *A Measurement of Neutrino Induced Charged Current Neutral Pion Production in the MicroBooNE Experiment*
- Julia Book, *Measurement of double-differential cross sections for mesonless charged-current neutrino scattering on argon with MicroBooNE*

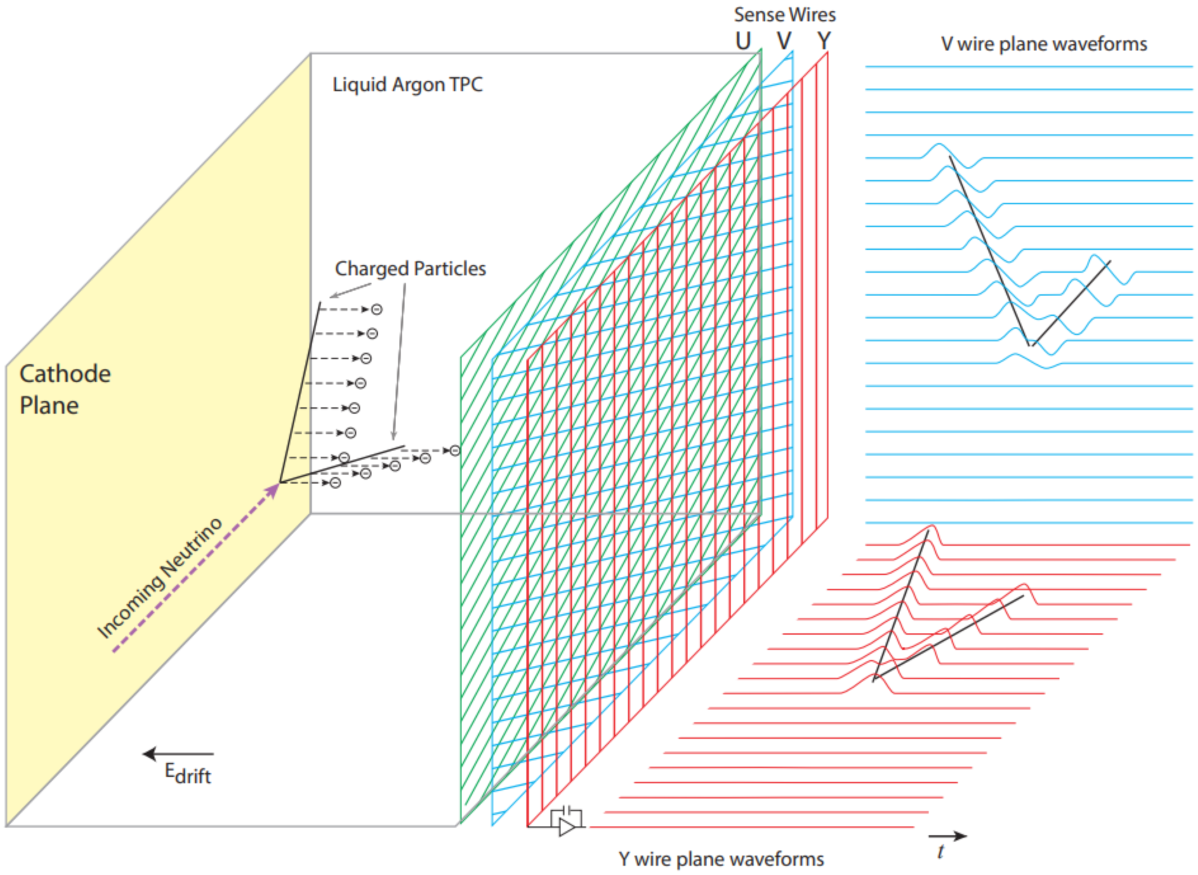
Thank you!

Backup

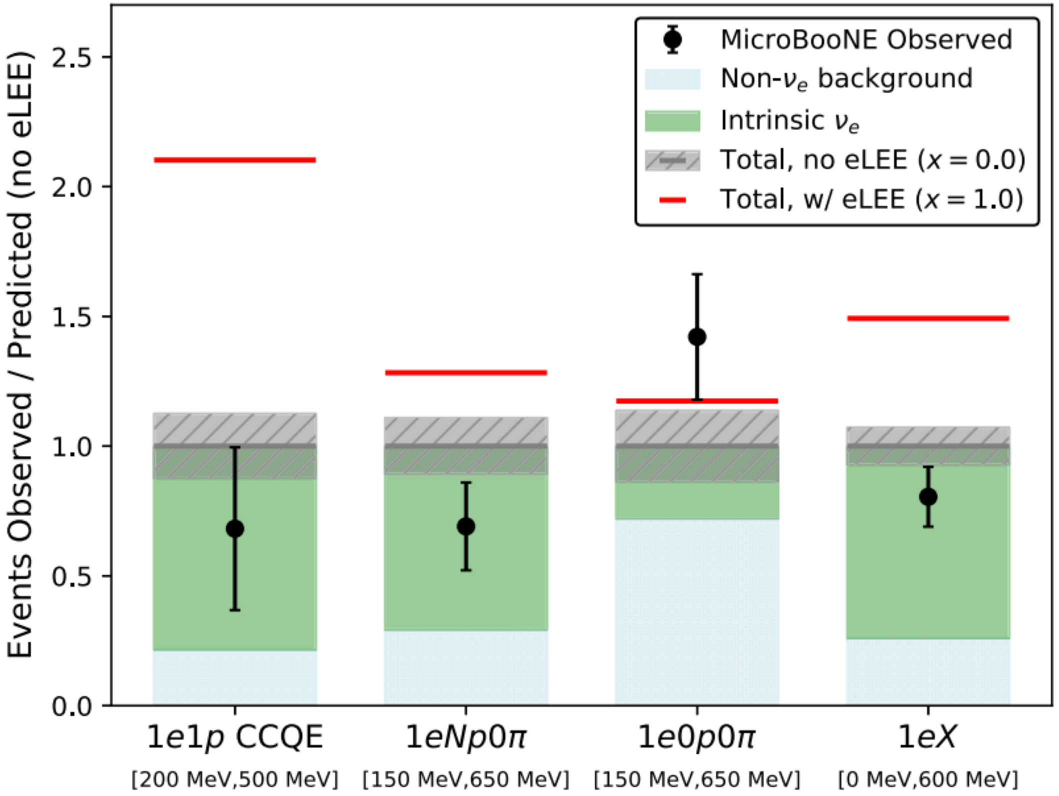
Principle of Single-Phase Liquid Argon Time Projection Chamber (LArTPC)

- ~mm scale position resolution with multiple 1D wire readouts
- Particle identification (PID) with energy depositions and topologies





eLEE Search Results



Total selected events and overlap

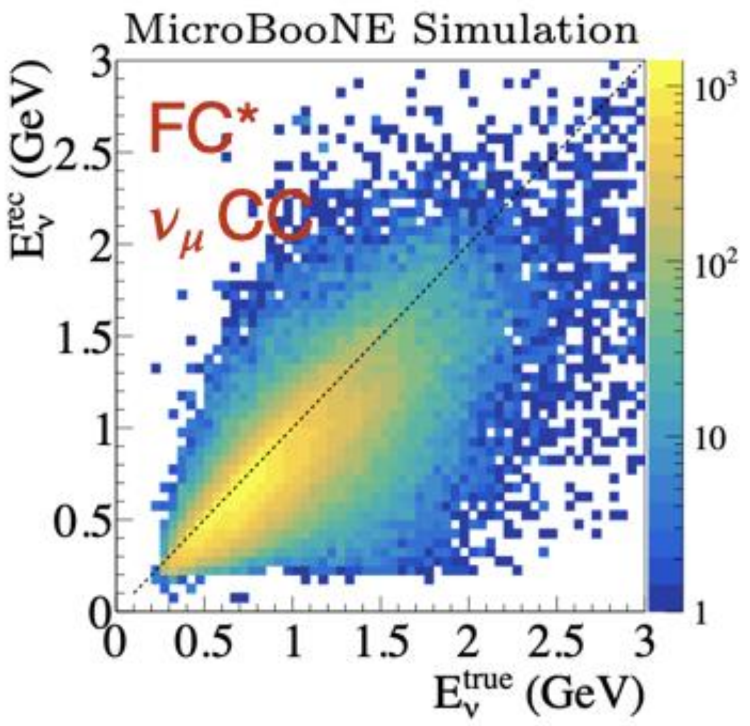
	$1e1p$ CCQE	$1eNp0\pi$+ $1e0p0\pi$	$1eXp$ (Fully contained)
Reconstructed E_ν (MeV)	200-1200	10-2390	0-2500
$1e1p$ CCQE	**25**	*9*	*14*
$1eNp0\pi + 1e0p0\pi$		**98**	*46*
$1eXp$ (Fully contained)			**338**

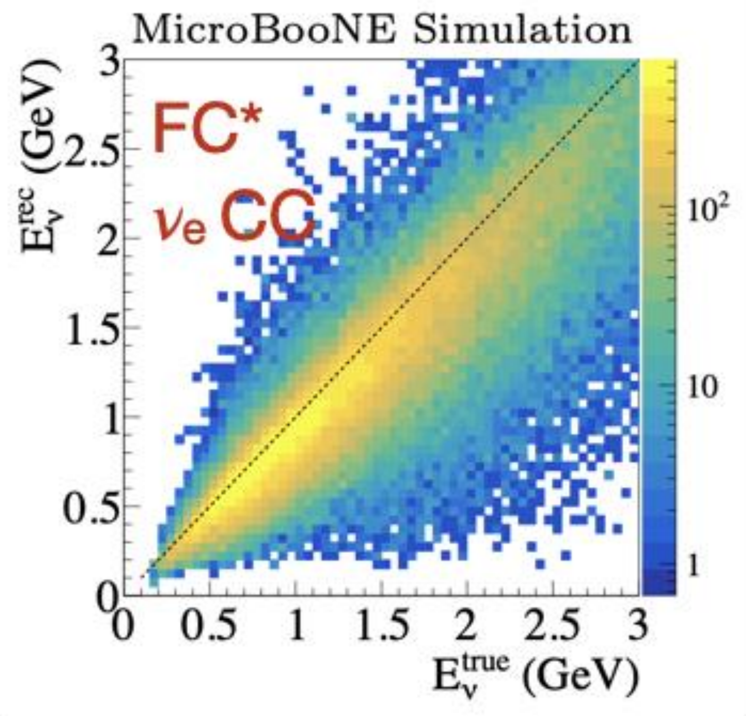
Signal-enhanced region comparison

	$1e1p$ CCQE	$1eNp0\pi$	$1e0p0\pi$	$1eX$
E_ν (MeV)	200-500	150-650	150-650	0-600
Predicted, no eLEE	8.8 ± 3.0	30.4 ± 6.1	19.0 ± 5.3	69.6 ± 9.4
Predicted, w/ eLEE	18.5 ± 4.4	39.0 ± 6.8	22.3 ± 5.7	104 ± 12
Observed	6	21	27	56

1eX analysis: Phys. Rev. D105, 112005 (2022)

Energy Resolution

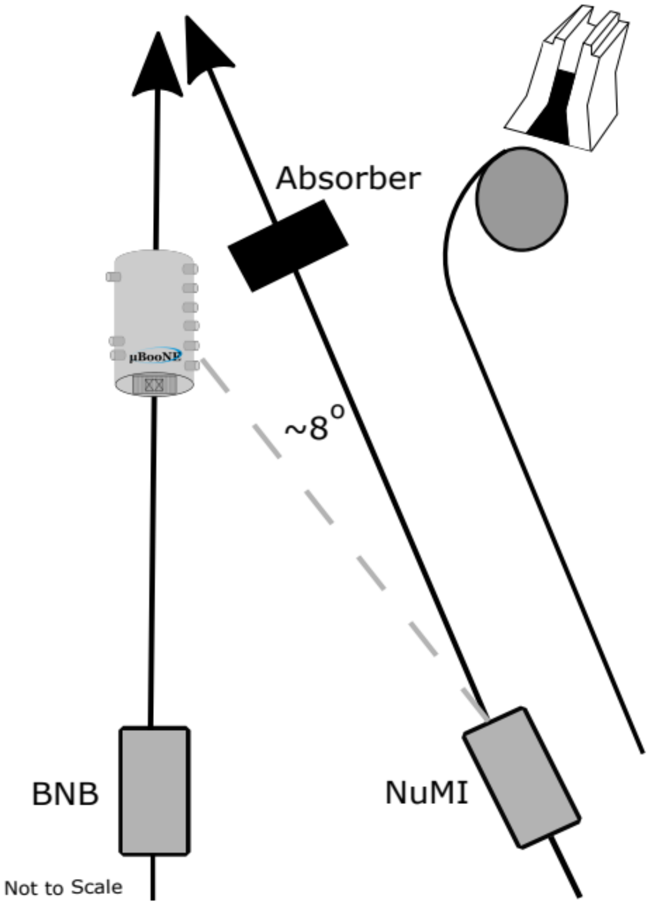


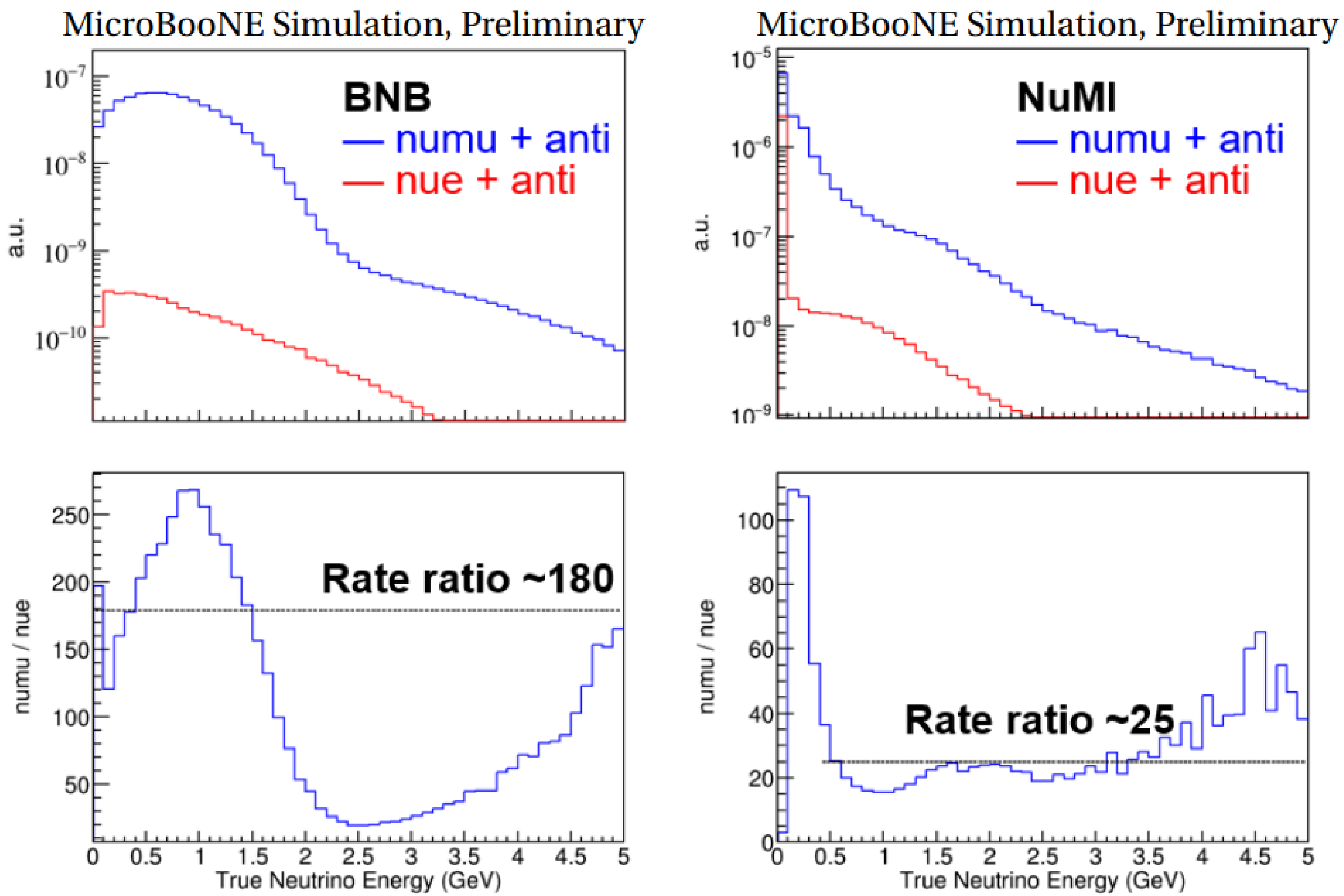


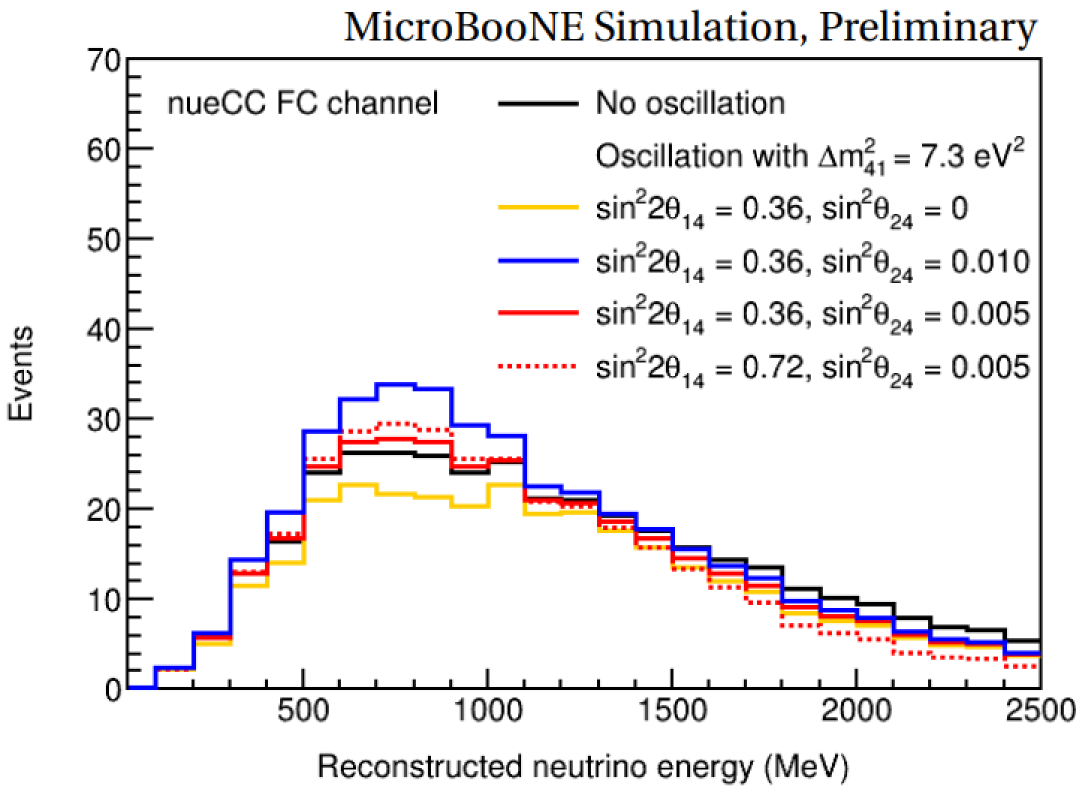
- 15-20% resolution for fully contained ν_μ CC
- 10-15% resolution for fully contained ν_e CC

Neutrino energy reconstruction primarily follows a calorimetric method

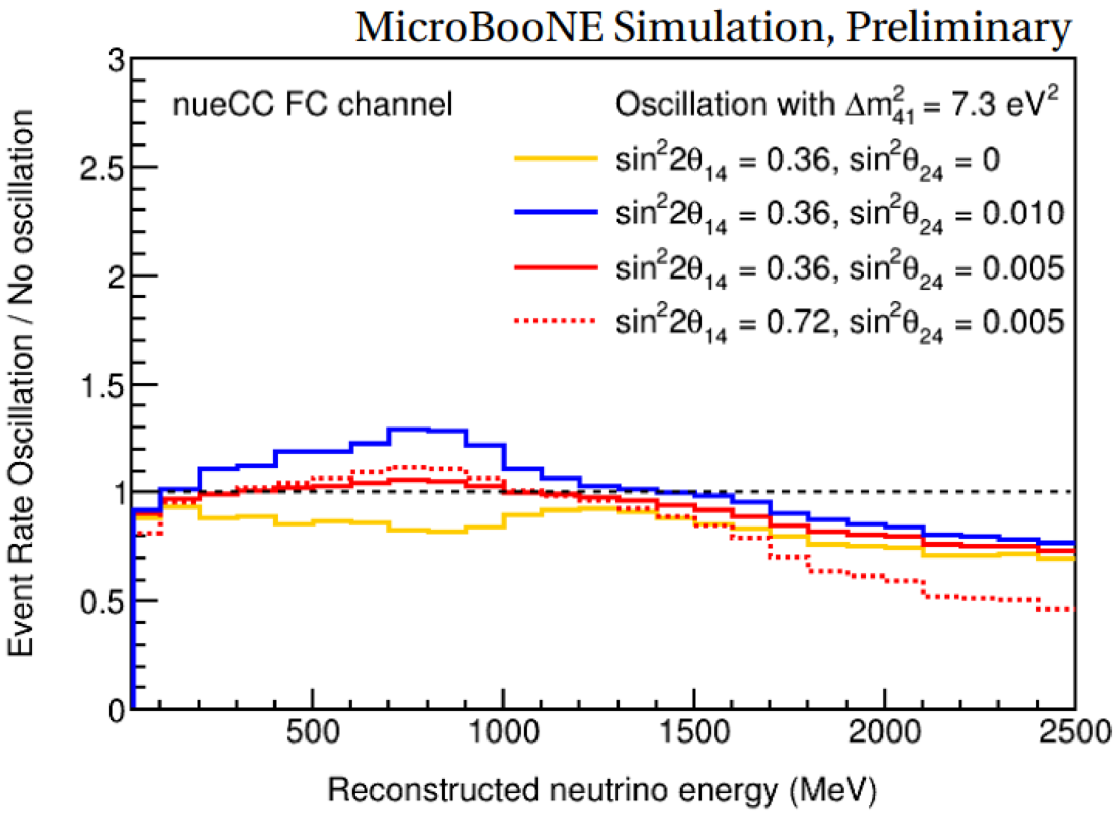
BNB and NuMI Neutrino Fluxes







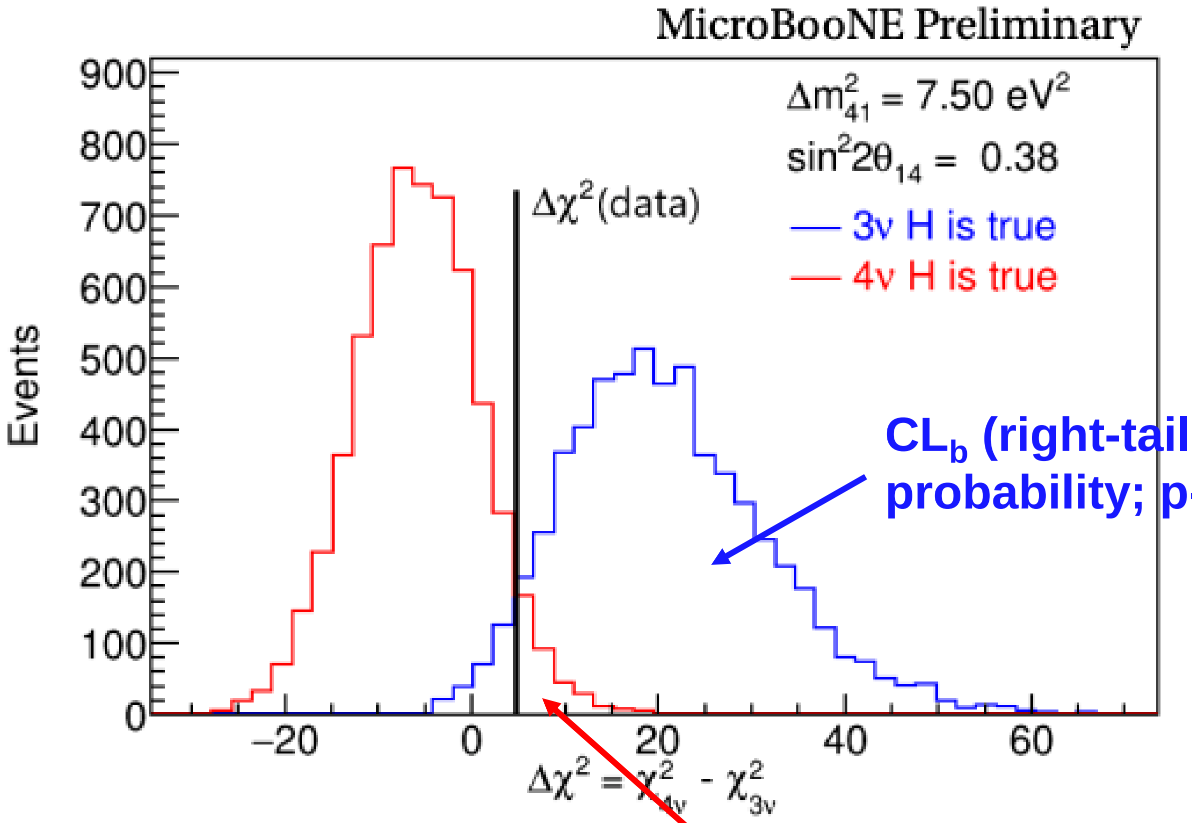
MicroBooNE Simulation, Preliminary
nueCC FC channel
No oscillation
Oscillation with Δm^2_{41} = 7.3 eV^2
$\sin^2 2\theta_{14}$ = 0.36, $\sin^2\theta_{24}$ = 0
$\sin^2 2\theta_{14}$ = 0.36, $\sin^2\theta_{24}$ = 0.010
$\sin^2 2\theta_{14}$ = 0.36, $\sin^2\theta_{24}$ = 0.005
$\sin^2 2\theta_{14}$ = 0.72, $\sin^2\theta_{24}$ = 0.005
Events
0
10
20
30
40
50
60
70
500
1000
1500
2000
2500
Reconstructed neutrino energy (MeV)



MicroBooNE Simulation, Preliminary
nueCC FC channel
Oscillation with Δm^2_{41} = 7.3 eV^2
$\sin^2 2\theta_{14}$ = 0.36, $\sin^2\theta_{24}$ = 0
$\sin^2 2\theta_{14}$ = 0.36, $\sin^2\theta_{24}$ = 0.010
$\sin^2 2\theta_{14}$ = 0.36, $\sin^2\theta_{24}$ = 0.005
$\sin^2 2\theta_{14}$ = 0.72, $\sin^2\theta_{24}$ = 0.005
Event Rate Oscillation / No oscillation
0
0.5
1
1.5
2
2.5
3
500
1000
1500
2000
2500
Reconstructed neutrino energy (MeV)

CL_s method

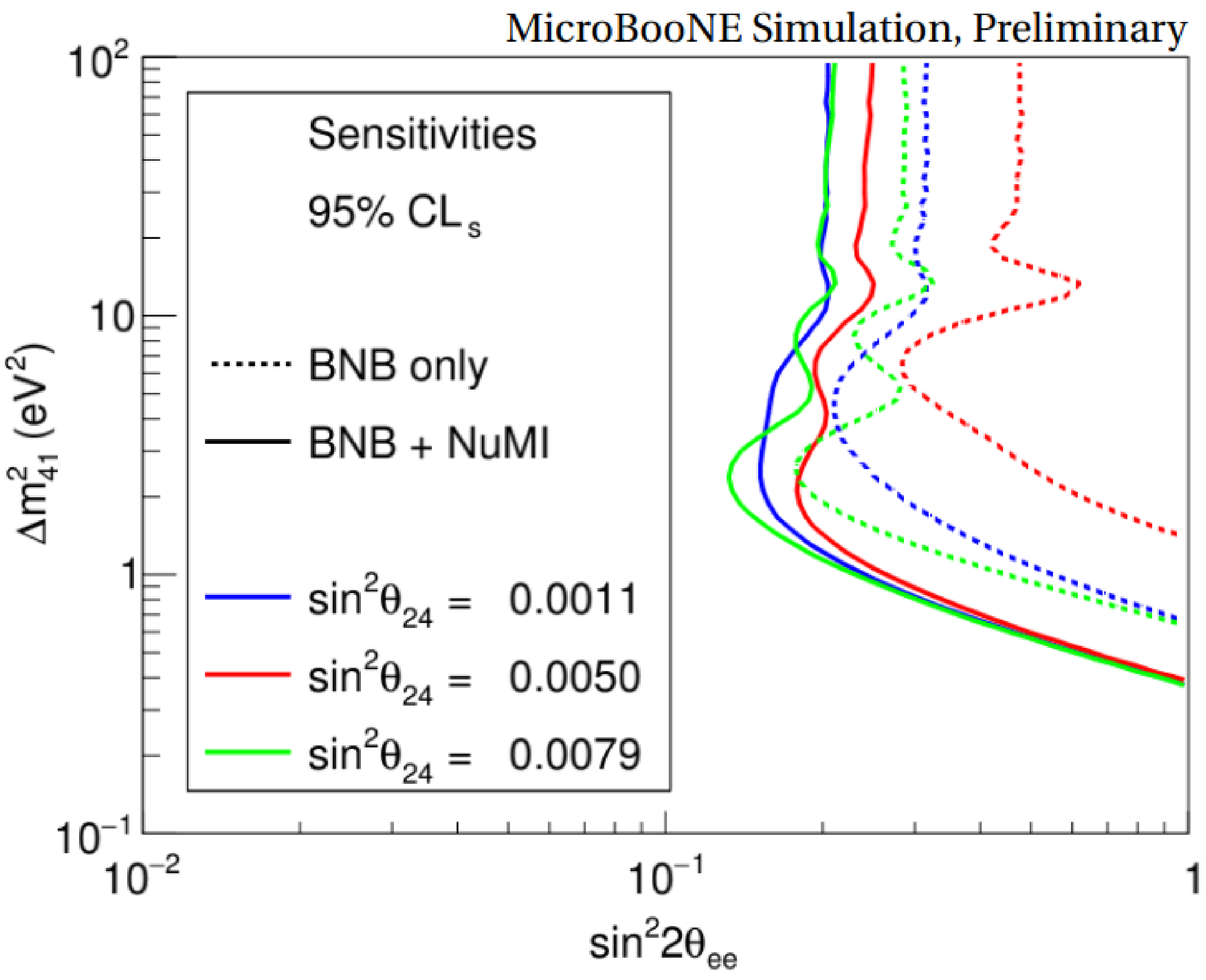
$\boldsymbol{CL_s = CL_{s+b}/CL_b = 1 - \alpha}$ *(confidence level)*



CL_b (right-tail probability; p-value)

CL_{s+b} (right-tail probability; p-value)

Degeneracy and Its Mitigation



BNB Run 1-3
NuMI Run 1

Mitigation by BNB+NuMI